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May 11, 1994

Steven E. Payne, Capt., USAF
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Dear Captain Payne:

RE: Capt. Paul K. Daly, USAF, 504-94-8629

As the graduate advisor and thesis chair for Cpt. Daly, I am pleased to inform you that he received his master's degree in psychology this spring semester. His performance at all times was excellent, as shown both in his coursework and his thesis research. He is truly one of our best students and the Air Force should be quite proud of his service and performance.

Capt. Daly carried a full academic course load of psychology and human factors courses, some of which were offered in the Department of Industrial and Systems Engineering, and received As in every course. In addition, he was always involved in independent research. His first research project was presented to the national scientific meeting of the Human Factors and Ergonomics Society in the Fall of 1993 in Seattle, Washington. His second research project, which was his master's thesis, is presently being revised for submission to a major journal.

For the above two mentioned projects, he became facile with the Micro Experimental Laboratory on a 386 computer. This required his preparing the presentation of stimuli and writing programs for their execution. He reviewed psychometric studies of cognitive abilities in his evaluation of the best cognitive predictors of performance on visuospatial computer tasks, as well as literature on workload and dual task performance. Both studies are major contributions to the literature on the effect of dual tasks on visuospatial performance in subjects varying in visuospatial skills. Theoretically, it contributes to our understanding of working memory and to the design of work environments which require fast and efficient responses that are either verbal or visuospatial in nature.

Cpt. Daly was also involved in a cooperative project dealing with the cognitive ability correlates of vigilant decision making with Dr. Robert Beaton in the Industrial and Systems Engineering Department. This Navy sponsored project assessed vigilant performance in high and low sustained attention work environments.

In addition to the above, Cpt. Daly also actively participated in other projects in my laboratory. He assisted in the spectral analysis of EEG brain waves during perceptual tasks and thereby learned basic concepts about electrical activity in the brain. He learned how to use the 24-channel Neurosearch-24 brain mapping system. Finally, he learned how to administer standardized scales of hypnotic susceptibility to adults in our study on the effects of hypnosis on enhanced attentional focusing.

Mental Rotation With and Without a Concurrent Task:
Moderating Effects of Visuospatial Ability

by

Paul K. Daly

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University in
partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Psychology

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MENTAL ROTATION WITH AND WITHOUT A CONCURRENT TASK:

MODERATING EFFECTS OF VISUOSPATIAL ABILITY

by

Paul K. Daly

Committee Chair: Helen J. Crawford

Psychology

Abstract

Men (N = 25) and women (N = 27) rated as either high or low in visuospatial ability as assessed on a battery of visuospatial tests (Card Rotations, Mental Rotations, Minnesota Paper Form Board), performed a computer-administered task requiring the mental rotation of abstract geometric shapes presented sequentially, either alone or with a concurrent task of repeating sets of six random digits. Gender and skill-level effects were found. Men were faster than women, and high visuospatial subjects were faster than low. Individual performance did not significantly differ between the single- and dual-task conditions, either in terms of mean response time or rate of mental rotation. This finding is counter to previous studies (Corballis, 1986; Kail, 1991) that found subjects performed slower overall in dual-task conditions, but did not differ in terms of rotation rate. Differences in group variability were also found; that is, women were more variable in response time and error rates than men, and lows

were more variable than highs. The gender differences are interpreted in terms of variability; with the major finding that for rotation rate, intercept, and errors, only within the low visuospatial skill category did women perform poorer than men. Furthermore, only women in the low visuospatial skill group showed the classic mental rotation function of increasing response time with increasing angular disparity.

Acknowledgements

I would like to thank the Air Force Institute of Technology for sponsoring my graduate study. I am also grateful to my committee members: Dr Crawford for allowing me use of laboratory space and stimulating my interest in cognitive science and visuospatial processing; Dr Prestrude for his advice and orientation when I applied and first arrived on campus; and Dr Beaton for allowing me research opportunities and being my liaison in the Human Factors and Ergonomics arena.

I also couldn't have survived this tour of duty without my friends Paige, Steve, Andrea, John, and Zane.

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Introduction

Individual differences in visuospatial skill are pervasive throughout the general population. The verbal/spatial dichotomy exists in many human endeavors; for example, creative pursuits (e.g., painting versus poetry), leisure activities (reading versus watching a movie, or playing video games), and professional life (engineering versus management). Often, people generally know where they fall on the spectrum; for example, many are quick to point out that they are not good at visuospatial tasks, and generally stay away from them. Visuospatial skills such as mental rotation are used in everyday tasks such as rearranging furniture, assembling jigsaw puzzles, and fitting together pieces of mechanical devices, as well as for problem solving in geometry, electrical engineering, stereochemistry, and theoretical physics (Cooper & Shepard, 1973).

Visuospatial skill has also been correlated with performance in certain industrial jobs (Ghiselli, 1973), scientific and art-related fields (Smith, 1964), and pilot training (Gordon & Leighty, 1988). Gordon and colleagues related differential performance on visuospatial or verbosequential tests to successful achievement in different groups; that is, more bank staff and health care managers had higher verbal than visuospatial skills (Gordon, Charns,

& Sherman, 1987), and more airport managers and computer programmers had higher visuospatial than verbal skills (Gordon, Charns, & Garamoni, 1984; cited in Gordon & Leighty, 1988). Dror, Kosslyn, and Waag (1993) found that U.S. Air Force pilots were better at mental rotation and metric spatial relations tasks than control subjects. The etiology of these individual differences is beyond the scope of this study, yet one possible explanation is that people solve visuospatial problems using certain strategies based on their experience or preferences, for example, verbal versus mechanical. If an inefficient strategy can be changed, visuospatial skill may be enhanced. Identification of procedures to change inefficient strategies could contribute to the design of effective visuospatial training procedures.

The following review will cover psychometric factors of visuospatial ability, focusing on the phenomena of mental rotation. The general concept of mental rotation, the basic experimental procedures used to study it, and specific findings will also be discussed. A brief overview of dual capacity theories of information processing, with respect to dual task performance, is presented. The review then leads to a discussion of the pilot study for the present research and present hypotheses.

Background

In contrast to verbal ability, which includes all components of language usage, visuospatial ability generally refers to "skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information" (Linn & Petersen, 1985; p. 1482). The difference between verbal and visuospatial ability is a fundamental dichotomy in most theories of human cognition and intelligence. Thurstone (1938) and French (1951) identified a *Space* factor that appeared in a variety of tasks involving perception of spatial relations and configurations. Vernon's (1961) hierarchial theory has two major group factors: *verbal-educational* ability which includes specific abilities such as creative, verbal, and numerical abilities; and *spatial-practical-mechanical* ability which includes psychomotor, mechanical, and visuospatial abilities. Guilford's (1985) structure of the intellect model also contrasts *semantic* and *figural* content. Lohman (1988) further decomposed spatial aptitude into three factors: *visualization*, a general visuospatial factor measured by complex tests such as the paper form board; *spatial orientation*, the ability to imagine a stimulus from another perspecive; and *speeded rotation*, the ability to perform rapid comparisons of rotated images, as measured by speeded tests such as the Card Rotations test.

Kosslyn (1988) stated that mental imagery has four distinct subsystems: 1) *generation* of an image from memory, 2) *maintenance* of the image over time, 3) *inspection* of the image to gain information, and 4) *transformation* of the image to "see" what would happen if the image was in a different orientation. One of the most studied processes of spatial transformation is *mental rotation,* or the process of rotating a mental image into a new orientation.

Mental Rotation

In 1971 Shepard and Metzler reported that "the time required to recognize that two perspective drawings portray objects of the same three-dimensional shape is found to be a linearly increasing function of the angular difference in the portrayed orientations of the two objects...(p. 701)." The "classic" linear slope for mental rotation is presented in Figure 1, which is adapted from Experiment 1 of Cooper and Shepard (1973) using alphanumeric characters. In general, the rotation rate was said to be about 60°/second (Metzler & Shepard, 1974).

The study was an important one in the reemergence of cognitive psychology since, as a counterargument to the behaviorists, here was a paradigm that yielded empirical, behavioral evidence of the existence and controllability of mental images, something heretofore measured only through introspective reports and self-report data (Cooper &

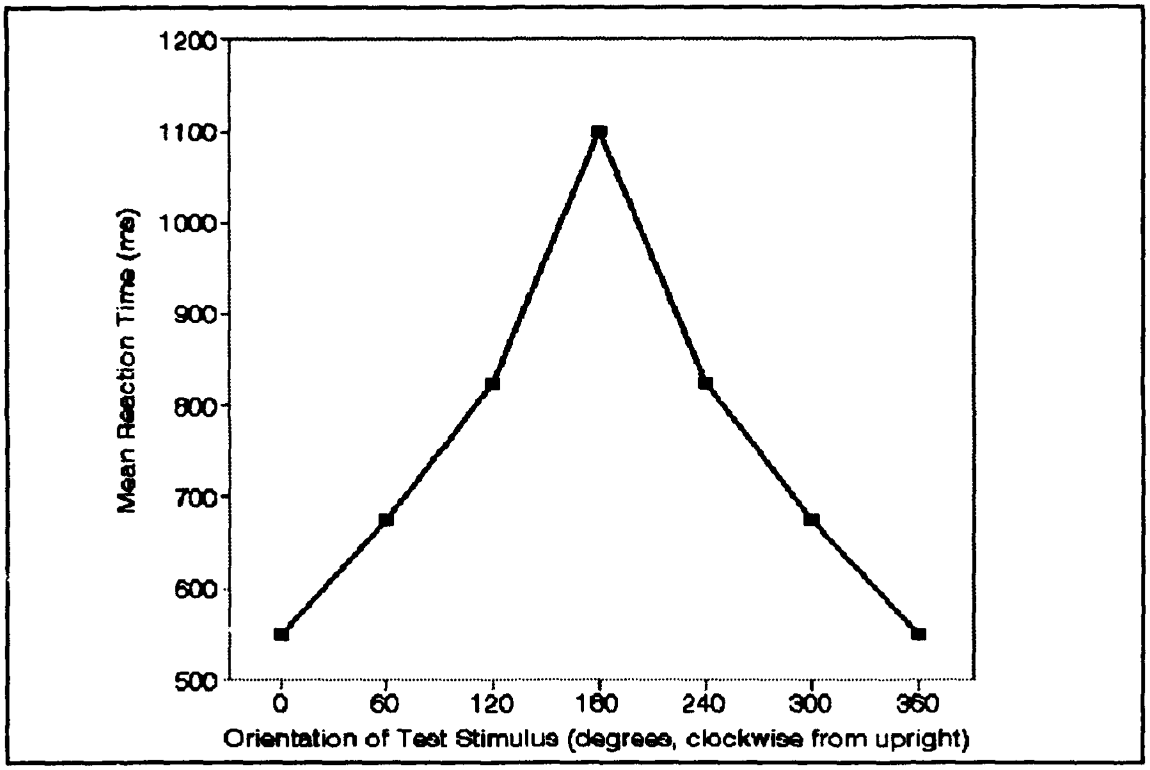

Figure 1. Classic mental rotation slope. (Adapted from Cooper & Shepard (1973) Experiment 1.)

Shepard, 1973). The notion that mental rotation was occurring was still an inference based on reaction time, yet the linearity of the function was inconsistent with other interpretations which could not explain why the increase was so linear, why it was the same for two- and three-dimensional stimuli, why it was the same for plane and depth rotations, and why the subjects themselves reported rotating the objects into congruence (Cooper & Shepard, 1973).

The interpretation from this and many other studies was that people mentally rotate objects in a manner analogous to

the actual physical rotation of the object (Kail & Pellegrino, 1985). Shepard (1975) termed this *second-order isomorphism*, meaning the internal representation or process has a one-to-one correspondence to the physical transformation of the external object, although not a first-order, structural relationship between the internal representation and a neurophysiological event. In this sense, the mental image passes through a trajectory of intermediate states, and each intermediate step of the internal representation corresponds with an intermediate stage of the external physical rotation (Kosslyn, 1988; Metzler & Shepard, 1974). Kosslyn (1988) found this surprising since images are not real objects and do not have to operate according to the laws of physics (i.e., instantaneous movement of an object from point A to point B is impossible; it must also pass through an infinite number of intermediate points between A and B). He suggested one reason we transform images incrementally is due to a categorical encoding subsystem that monitors image transformations, which requires gradual changes to avoid "overshooting" the correct orientation.

However, some studies identified subjects who did not show the classic slope; that is, they did not show increased response time with increased angular disparity between stimuli. Dror, Kosslyn, and Waag (1993; Dror, 1992) found a

subgroup of U.S. Air Force pilots who yielded a flat slope (mean slope less than -.5 ms/degree) on a sequential mental rotation task. Dror (1992) suggested an alternative process of single-step mapping was employed; the starting position is directly transformed into the final position without intermediate steps. However, it may also be possible that pilots are better at other visuospatial skills, for example, accessing visuospatial information in memory or shifting locations of representations (Dror, Kosslyn, & Waag, 1993). Cohen and Kubovy (1993) found that subjects can be influenced to perform "mental rotation" tasks rapidly, that is, at a latency nearly independent f slope, under conditions of fewer stimuli and pressure to meet a response time "deadline".

Individual Differences

Individual differences are evident in almost any visuospatial task; some individuals solve the problem quickly and accurately while others make errors, take a long time, or find a nonspatial strategy (Carpenter & Just, 1986). According to Kail and Pellegrino (1985), high-visuospatial skilled individuals perform mental transformations more rapidly than low-skilled individuals, partially due to more proficiency during the encoding phase, which they report is also a source of differences in inductive reasoning.

However, the natural inclination within each individual towards either verbal and visuospatial propensities may also be a source of variability. People who score higher on verbal than visuospatial tests may have a bias towards using a verbal, analytic strategy to solve visuospatial problems; and more visuospatially-oriented individuals may favor holistic visuospatial strategies. Individual d rences in strategies have been reported in many studies oι mental rotation.

<u>Strategies</u>.

Cooper and Shepard (1973) acknowledged that other processes may be used to determine identical objects; for example, visual search, feature detection, verbal analysis, or some other form of "digital computation". They tested this against their hypothesis of analog rotation by having the subjects imagine a letter rotating at a constant rate, and then presented the stimulus (alphanumeric characters) in either the *expected* orientation or at a *different* angular orientation. They found flat slopes when the stimuli appeared in the expected orientation and increasing reaction times as the stimuli departed from the expected orientation. This led them to conclude that actual rotation of the image was taking place, and that it was an analog process. However, subjects received extensive practice and they had performed in previous experiments in addition to the 4 hours

required for this experiment. Thus, the subjects may have learned the most efficient strategy to solve the problems and individual differences may have diminished.

Hock (e.g., Hock, Gordon, & Gold, 1975) argued there are two different strategies for mental rotation: a *structural* strategy influenced by stimulus orientation, and an *analytic* strategy that relies on verbal code. These distinctions were based on post hoc analyses of data on a letter-matching task where the stimuli were either standard or rotated 180°: those with large rotation effects were said to have emphasized a structural strategy, whereas those with small rotation effects were said to have used an analytic strategy. Cooper (1976, 1982) used a research paradigm in which response (i.e., same or different/mirror) and similarity of the mirror-image stimuli (six levels of variation, rated from "highly similar" to "highly dissimilar") for abstract shapes were manipulated, in order to identify subjects who used one processing strategy or another. She found that subjects' performance in a mental rotation task conformed to one of two qualitatively distinct patterns. One subgroup was characterized as using a *holistic* strategy, in which the subjects did not show an effect of "different" [mirror-image] stimulus similarity. This subgroup presumably used a parallel comparison process to compare test shapes with memory representations with the

goal of achieving a match, whereby the "same" response would be executed. A second group, characterized as *analytic*, had monotonically decreasing response times with decreasing similarity between the standard shape and the test probe.

Cooper (1982) suggested that the latter subjects could be using a more analytic, dual-comparison process in which in addition to the holistic comparison, subjects would simultaneously compare specific features of the test probe and the memory representation, which would produce a "different" response as soon as a distinguishing feature was found. In this case, subjects would take less time to generate a "different" response to highly dissimilar stimuli. Thus, the *holistic* strategy involves the rapid, parallel comparison of a memory representation with a visual shape with little analysis of difference information; whereas the *analytic* strategy detects features that differentiate memory representations from visual stimuli.

Carpenter and Just (1986) suggested that at least three processes can be used in any visuospatial test: *rotation*, *perspective change*, and *nontransformational*. The first two correspond with Lohman's (1988) spatial orientation and speeded rotation subfactors, whereas the latter may be due to some nonspatial or verbal process. Further, they argued, factor analyses of psychometric visuospatial ability assume that all subjects use the same strategy, for every problem,

on visuospatial tests; this may be one source of confounding, and the reason for low correlations between visuospatial test and task performance (Carpenter & Just, 1986).

Schultz (1991) developed a questionnaire to assess three solution strategies which could be used for solving any visuospatial problem: mental rotation, perspective change, and analytic. She found strategy to account for a significant amount of variance (roughly equal to gender) for mental rotation and spatial orientation tasks. Carpenter and Just (1986) correlated subjects' retrospective strategy reports with patterns of eye movement to examine individual differences in performance on three-dimensional mental rotations tasks (Cube Comparisons Test and Shepard & Metzler mental rotation task). They found that low visuospatial subjects used a longer trajectory to rotate, lost track of cube sides not in their mental image, and were more likely to rotate noncorresponding segments into congruence.

Lohman (1988) found that subjects shifted strategies on various trials during a Card Rotations Test. For trials in which subjects used a rotation strategy, response time showed the typical slope, whereas for trials where subjects reported using some other strategy response times showed a different pattern: in particular, these subjects' reactions times were much faster for trials in which the stimuli

differed in angular disparity of 90, 180, and 270 degrees (i.e., the cardinal points of the compass). Presumably, responses are faster since the stimuli can be encoded more easily as pointing "right", "down", or "left"; and stimuli may also be "flipped" about the axes to determine if they match.

Gender Differences.

Generally, women have been found to have better verbal abilities (e.g., word fluency, grammar, spelling, reading, verbal analogies) than men, while they have been found to have poorer visuospatial abilities (for review see Halpern, 1992). Specifically, men tend to outperform women consistently in tests that are markers for spatial orientation and speeded rotation factors. Many studies have found a marked difference favoring men on mental rotations tasks (Bryden, George, & Inch, 1990; Halpern, 1992; Kail, Carter, & Pellegrino, 1979; Lohman, 1986). Furthermore, strong correlations have been found between various measures of visuospatial ability and mathematical or quantitative ability (for review see Halpern, 1992). Accordingly, consistent gender differences favoring men have also been found in quantitative tests such as the Math portion of the Scholastic Achievement Test; that is, men outscore women by about 50 points (National Education Association, 1989).

However, Kail, Carter, and Pellegrino (1979) contended

that the important difference is not average level of ability, but variability within each gender; they found that women's performance on a mental rotation task was more variable than men's. Halpern (1992) suggested that differences in variability may indicate differences in the way men and women perform visuospatial tasks. For example, women may be using more varied strategies (e.g., verbal labels v. visualization) while men may be more homogeneous in their strategies. Bryden et al. (1990) found that despite gender differences there was considerable overlap between men and women in slope, with about two-thirds of the men falling in the "fast rotator" distribution (i.e., 20 ms/degree) and two-thirds of the women falling in the "slow rotator" group (i.e., 30 ms/degree). Lohman (1986), congruent with Bryden et al. (1990) and Kail et al. (1979), found women to have a bimodal distribution of slopes, with 30% of the women having slopes outside of the male distribution. These findings suggest that gender differences may be attributable only to those women at the low end of the visuospatial spectrum.

Just as individual performance differs on various tests of visuospatial ability, performance on mental rotation tasks varies due to different task demands and experimental manipulations. Some of these are discussed below.

Mental Rotation Experimental Paradigms

Many studies have examined different aspects of mental rotation by manipulating different variables. Types of stimuli, stimulus complexity, presentation order, or task-induced strategy can affect performance on mental rotation tasks. The following subsections review such findings.

Stimuli.

Studies have used unfamiliar stimuli (abstract shapes or cubes) and alphanumeric characters. Subjects who compared unfamiliar stimuli with no standard upright orientation, for example, snakelike cubes (Shepard & Metzler, 1971) or abstract polygons (Cooper, 1975), showed reaction times as linear functions of angular orientation. Alphanumerics (i.e., "F", "7") are well encoded and only the test probe needs to be presented in a trial; these paradigms can be categorized with sequential or successive presentation (see *Presentation Condition* below). However, for letters or numbers with a standard upright orientation, response time functions are nonlinear, possibly due to the fact that discriminations could be made when the shape is slightly tilted from upright (Cooper & Shepard, 1973). Differences such as these make it difficult to compare slopes between different experiments.

Furthermore, task demands may encourage one strategy over another. Finke and Shepard (1986) suggested that one

must arrange the task to encourage holistic rotation. Strategies based on descriptions of individual parts can be discouraged by requiring discriminations between objects that share all features except their globally enantiomorphic (mirror image) structures, and by displaying three-dimensional objects in a variety of orientations. A strategy of rotation of one part at a time may be discouraged by requiring a fast match-mismatch response, and by using test objects identical to the target or differing by subtle, random perturbations (see Cooper, 1982). Also, when two objects are simultaneously presented, the subject can imagine rotating each part separately.

Complexity.

Cooper (1975, 1976) found no increase in slope with increasing complexity of random polygons (Attneave type) of 6 to 24 vertices. She suggested that since mental rotation is a holistic process, rotation rates should not depend on pattern complexity. However, these studies used subjects with extensive practice. It may be true that subjects more familiar with a figure will rotate it holistically, and at a rate less dependent on complexity. Individual differences in visuospatial ability were not considered in these studies.

S. Shepard and D. Metzler (1988) compared three-dimensional figures as used by Shepard and Metzler (1971)

and two-dimensional figures as used by Cooper and Shepard (1973). They found that the difference in rotation rates was due mainly to presentation condition, that is, rate of rotation was three times faster for the single-stimulus task (i.e., successive--comparing a test probe with a well-learned memory representation) versus simultaneous (i.e., Shepard & Metzler (1971) task). Three-dimensional shapes required more initial encoding, but once encoded were rotated as rapidly as the two-dimensional shapes.

Presentation Condition.

Simultaneous discrimination tasks provide sufficient information in the frame to make the discrimination, whereas successive tasks require the subject to integrate information from a prior frame. Successive tasks place more demands on working memory and require more mental effort or attentional capacity (Davies & Parasuraman, 1982). In a study comparing simultaneous versus successive presentation, Steiger and Yuille (1983) presented figures in pairs for one condition, while the second condition had the subjects memorize the stimulus figure for 2 minutes, after which they were presented only with the test figures. They found that the simultaneous condition yielded the classic linear slope (10.2 ms/degree) while the memory condition had a flatter slope (2.1 ms/degree). These results were replicated by Cohen & Kubovy (1993). Simultaneous tasks may also inflate

response times, since subjects may also look back and forth between features of objects.

Practice.

Kosslyn (1988) found large practice effects, even within the space of an hour, were typical for imagery tasks. For instance, practice improves activating a given imaged object but does not transfer greatly to other imaged objects. Kail and Park (1990) found that rotation rate for children, but not adults, decreased substantially over extended practice (3360 trials)on a letter mental rotation task, but this practice did not transfer to rotation of abstract characters or to a memory search task.

Such findings are counter to a *process-based* theory of mental rotation practice, which would predict that rotation should be independent of the "familiarity" of stimuli. Kail and Park (1990) suggested an *instance-based* explanation: practice reflects a shift from the use of algorithms for performing a task to a reliance upon memory for previous solutions. Practice produces more representations of the stimulus and its associated response, making it more likely that the solution will be retrieved rather than computed. This finding may complicate interpretations of response times on mental rotation tasks, since subjects may be relying on memory of prior trials to respond, rather than "mentally rotating" the stimuli into congruence.

Dependent Variables of Mental Rotation Tasks.

Slope. Several studies report subject performance in terms of the slope of the function relating response time to angular disparity. Carpenter and Just (1986) defined rotation rate as the rate at which visuospatial orientation is executed; in general, the increase in response time is a function of the number of transformations. Dror, Kosslyn, and Waag (1993) state that slope can be used to examine the rotation process itself, independent of the processes involved in encoding the stimulus and generating the response (which are reflected by the intercept). Dror (1992) cites rotation rate as an indication of efficiency of rotation. This reasoning suggests that the flatter the slope, the more efficient the mental rotation process.

However, Lohman (1988) argued that slope can be a poor estimate of rate of rotation because it may not be obvious which direction the stimulus should be rotated, and the subject may loose track and start over again. These two possibilities are more likely for large (e.g., 180°) than small (e.g., 60°) rotations.

Accuracy. One of the problems with the interpretation of mental rotation studies, or with any chronometric study, is that error trials are discarded and error rate may or may not be reported. Pachella (1974) described several procedures that have been used to handle errors: ignore

them, try to induce the same error rate for all subjects (e.g., by emphasizing accuracy or making the task easier), or use statistical approaches such as analysis of covariance or multivariate analysis of variance. Another approach (see Lohman, 1988) involves repeating error trials later in the experiment, hoping the subject gets them correct.

Egan (1978) found that accuracy was the best measure of visuospatial ability for a spatial orientation and a mental rotation task (i.e., Shepard & Metzler, 1971). He found accuracy scores to be correlated with visuospatial test and pilot training performance, whereas rotation rates (slopes) and total response times were not. Some errors may be attributed to the initial encoding stage, where the subject chooses parts of the stimulus and compares them (Just & Carpenter, 1976). If the subject chooses non-corresponding parts and attempts to rotate them into congruence, he or she may incorrectly decide the figures are not the same. This is another example of how a non-holistic strategy may be inefficient. Also, as previously mentioned, Kail and Pellegrino (1985) attribute individual differences in visuospatial ability to differences in encoding processes and strategies. Thus, errors of commission may signal non-rotational strategies, as does very rapid performance for easily labeled orientations (e.g., 0°, 180°) (Lohman, 1988). Accuracy reflects success in selecting, sequencing, and

coordinating component processes, as well as executive processes such as encoding, maintaining, and transferring information between processes (Carpenter & Just, 1986).

Variability. Ackerman (1987) found interindividual variability of performance (i.e., reaction time (RT)) decreases with practice, since between-subjects' standard deviations were reduced after practice. However, this also depends on the task condition; if the task precludes development of automatic processing, RT variability remains constant or may increase over practice, even when mean RT decreases (Ackerman, 1987).

Dual-task methodology has been used in some information processing studies to further explore the nature of cognitive processes. The following overview describes such methodology, leading up to dual-task research on mental rotation.

Secondary Tasks

The secondary task paradigm used in workload measurement typically assesses fluctuations in secondary task performance as an estimate of workload or spare processing capacity afforded to the primary task (i.e., the task of interest) (for reviews see Gopher & Donchin, 1986; Wickens, 1992). The underlying assumption is that the operator has a fixed pool of resources and the processing

demands of a concurrent task reduce the available processing capacity. However, multiple-resource theories of information processing (e.g., Wickens, 1992) predict that interference will be minimized if the two tasks place demands on separate resource dimensions, including processing stage (early v. late), sensory modality (auditory v. visual) or processing code (spatial v. verbal).

Similarly, Baddeley's (1986, 1992) working memory model conceptualizes a system of three interacting components that temporarily store and manipulate information. The *central executive* component guides and controls the processing of information in two "slave systems": the *articulatory rehearsal loop* and the *visuo-spatial sketchpad* that temporarily store and manipulate information; for example, rehearsing verbal information and performing mental imagery tasks, respectively. As with Wicken's multiple-resource theory, the working memory model suggests that dual task performance can be maintained if the tasks involve separate systems. However, the central executive's resources can also be drained if the articulatory or visuospatial tasks are difficult. For example, Baddeley and Hitch (1974) found that speed of grammatical reasoning slowed with concurrent *articulatory suppression* tasks (repeating the word *the*, repeating the sequence "1,2,3,4,5,6", to repeating sequences of random digits). Performance showed the greatest deficit

with the random digits rehearsal task since it involved an added memory component, which more strongly taxed the articulatory loop and interfered with the central executive's functions of reasoning and initiating decision processes.

Articulatory suppression hinders the subjects from rehearsing verbal material and from registering visually presented material in the phonological store (Baddeley, 1986; 1992). In this sense, it may improve performance in some instances, such as for word recall for longer words (i.e., by reducing the *word-length* effect) and similar-sounding words (by abolishing the *acoustic similarity* effect) (Baddeley, 1986; 1992).

Logie (1986) found an analogous effect with the visuo-spatial sketchpad. He found that a matrix-matching task, as well as simple presentation of unattended visual information (i.e., random matrices with no matching task, plain colored squares, or line drawings of common objects and animals) interfered with concrete-word recall using a visual imagery mnemonic, but not with rote rehearsal. Other studies with the visuospatial sketchpad found that a pursuit rotor tracking task disrupted performance on a spatial matrix-recall task, while having little effect on a matrix-recall task involving verbal encoding (Baddeley, 1986).

Thus, a secondary task can degrade performance on the

mental rotation task if it is difficult enough to draw resources away from the primary task. But if primary task performance is maintained, there may be a number of interpretations: the secondary task may not be difficult enough, the primary task may be *automatized* and require less resources, or the secondary task may draw on a separate resource. Further, the secondary task may interfere with an unmeasured peripheral process, such as a verbal or visuospatial cognitive strategy, which may improve or degrade performance on the primary task depending on which strategy is more efficient for that particular task.

Dual-Task Studies of Mental Rotation.

Two studies have examined the effect of concurrent memory tasks on mental rotation performance to evaluate whether mental rotation is a controlled or automatic process. Memory tasks, such as the Sternberg (1966) task and the digit-span task, are considered to impose their heaviest demands on central processing resources (O'Donnell & Eggemeier, 1986). Corballis (1986), using a within-subjects design, examined the effect of a concurrent digit recall task (a verbal task), a matrix recall task (a visuospatial task), or no concurrent task on rotation of uppercase letters (a successive discrimination task). He found concurrent tasks slowed overall rotation time (RT), but did not influence the rate (i.e., slope) of rotation.

Kail (1991) found the same results with a similar study. Both studies reported no significant differences between the effects of the verbal and spatial memory tasks. It was concluded that mental rotation is an automatic process; attentional control may be necessary to set up the mental structures required in mental rotation (i.e., encoding and response generation), but actual execution of the mental-rotation component (i.e., as measured by slope) can be relegated to subordinate systems which do not compete for resources (Corballis, 1986).

However, both studies used a within-subject design, that is, subjects received both conditions in counterbalanced order. Within-subjects designs are problematic in mental rotation studies if asymptotic performance levels are not achieved through practice trials before the experimental conditions are presented. Indeed, the effect of order of presentation was significant in both studies. Further, another within-subject study by Dror and Chang (1993) attempted to induce rotation strategy by presenting figures in the same angular orientation over consecutive trials. They found that regardless of which condition was presented first, subjects performed faster in the second block (they were also unable to induce a direct translation strategy).

If response times and slopes are the variables of

interest, they can be confounded by practice effects. The solution is to present subjects with sufficient practice to reach asymptotic performance, or to look at the practice effects themselves and make between-subject comparisons.

Pilot Study

A pilot study (Daly & Crawford, 1993) used a between-subjects design to examine the effects of stimulus presentation time and concurrent tasks on mental rotation task performance, and also to determine which cognitive tests may predict performance. The study attempted to replicate Dror's (1992) finding of flat mental rotation functions for pilots, using high- and low-visuospatially skilled subjects. Dror's (1992) subjects all received self-paced sequential presentation of test stimuli. It was hypothesized that presentation time may have a differential effect on mental rotation response time for those with high- or low-visuospatial skill.

University students (N = 58; 32 women and 26 men) were screened on six paper and pencil tests: the Minnesota Paper Form Board Test (MPFBT; Likert & Quasha, 1941) to measure the visualization factor; the Mental Rotation Test (MRT; Vandenberg & Kuse, 1978), and the Card Rotations Test (CRT; Ekstrom, French, Harman, with Dermen, 1976) to measure 3-dimensional and 2-dimensional speeded rotation, respectively; the Finding A's Test and Identical Pictures

Test (both Ekstrom et al., 1976) to measure verbal and visuospatial perceptual speed, respectively; and the Rey Auditory-Verbal Learning Test (see Shapiro & Harrison, 1990) to measure verbal working memory. Only the three visuospatial tests were found to be significantly correlated with mean response time on the rotation task (MPFBT $r = -.36$, MRT $r = -.47$, CRT $r = -.48$; $p < .01$).

Subjects were split into groups of high and low visuospatial skill at the median combined z-score on the MRT and MPFBT and randomly assigned to each of two conditions: fixed- or self-paced presentation, and concurrent digit-span task or single-task. Subjects were then presented with computerized mental rotation trials of successively-presented abstract polygons (a more detailed description follows in the Methods section below). For the fixed-presentation condition, subjects had 2 seconds to study the first shape, whereas subjects in the self-paced condition had as much time as desired. Following a block of practice trials, there were two blocks of 48 trials each. The first block was always a single-task block, but for the second block half the subjects in each condition were asked to repeat out loud a series of six digits while they were doing the mental-rotation trials, and they were asked to write down the digits every 15 trials.

There was no effect of presentation time or concurrent

task on mean response time (RT), but there were effects of skill, gender, and angle. The mean RT results conflicted with those of Corballis (1986) and Kail (1991); subjects with the dual task did not differ in mean RT from subjects with only the single task. Slopes and intercepts were also analyzed for each of three skill levels (high, medium, and low, based on CRT performance). Overall, a practice effect was found: low visuospatially-skilled subjects had both lower (faster) intercepts and slopes in the second block, while the medium and high visuospatially-skilled subjects had only significantly faster intercepts in the second block. This suggests that regardless of which condition (single- or dual-task) was presented in the second block, subjects' encoding, comparison, and response times became faster, but mental rotation rate increased only for the low-visuospatial subjects.

However, there were no differences within each skill level between those who had the dual-task versus those who had the single-task. When slopes and intercepts from the first block were compared to those in the second block for each condition (single- v. dual-task); lows (n = 8), mediums (n = 11), and highs (n = 10) who received the dual-task condition all had significantly faster intercepts in the second block than those in the single-task condition. However, of the subjects who received two single-task

blocks, only the mediums had faster intercepts in the second block. When difference scores (block 1 RT minus block 2 RT) were compared, only lows increased their response speed while response times for mediums and highs stayed the same from block 1 to block 2. Furthermore, there was a trend for those who performed the dual-task to have higher difference scores than those who had two single-task blocks. For example, those in the high-skill, single-task group were actually slower in the second block. The average difference in RT (i.e., decrease from block 1 to block 2) was -23 ms for the single-task group and 183 ms for the dual-task group ($t(17) = -2.21$, $p = .041$).

An investigation of the performance of one subject in the low group underscored this point. The subject required 16 practice trials to reach the 80% accuracy criterion, and went from RT = 1469 ms + 7.59 x (angle) to RT = 1436 ms - 0.51 x (angle) when given the concurrent articulatory suppression task. This subject's rotation speed (i.e., the intercept) stayed the same, but rotation rate (i.e., slope) decreased dramatically. If slope is related to efficiency of rotation, this may suggest that concurrent tasks lead to increased efficiency. How? Possibly if the subject was using an inefficient strategy and the concurrent task interfered with this strategy.

Purpose and Hypotheses

The goal of the present study was to investigate the hypothesized differential effects of a concurrent articulatory suppression task on performance of a mental rotation task, as moderated by high and low visuospatial skill. Further analysis examined individual differences in terms of the relation between cognitive strategies and performance under different conditions of task load.

The present study was an extension of the pilot study, with certain enhancements. A larger group of subjects was screened to ensure greater differentiation between high and low skill levels. Methodologically, task condition (single or dual) was presented as a within-subject variable in counterbalanced order. An additional familiarization block was presented before these two task conditions to ensure subjects had reached an asymptotic performance level. Power was increased by doubling the number of trials in each block, and experimental control was increased by standardizing presentation time for all subjects and assessing digit-recall more often within the dual-task block.

This study utilized a mixed-factorial design. The between-subjects factors were: condition *order* (single- then dual-task v. dual- then single-task), visuospatial *skill* (high v. low), and *gender*. Within-subjects factors were:

angular disparity (0, 60, 120, 180, 240, 300 degrees), nested within object *congruency* (same v. different), nested within block *condition* (familiarization, single-task, or dual-task) which was nested within skill and gender. There were four dependent variables of interest: response time, errors, and the slope and intercept of the function of response time regressed on angle.

Hypotheses

Hypothesis 1. Various studies (e.g., Gordon & Leighty, 1988) have compared visuospatial test and task performance to demonstrate individual differences. Congruent with these findings it was predicted that low visuospatial subjects would have more errors, slower response times, greater (i.e., steeper) slopes, and more variability in response times than highs. It was also hypothesized that lows would also report more nonspatial strategies.

Hypothesis 2. Consistent with Corballis (1986) and Kail (1991) and other dual-task performance studies, it was predicted subjects would have more errors and slower response times in the dual-task condition than in the single-task condition. Subjects in the dual-task condition were expected to report more holistic rotation strategies, based on the prediction that verbal tasks interfere with analytic strategies. If the dual-task forces subjects to use more homogeneous strategies, subjects in the dual-task

condition should show less variability and flatter slopes than those in the single-task condition.

Hypothesis 3. Since research suggests that low visuospatial subjects are more variable in strategy than high visuospatial subjects, and with the prediction that a verbal task would reduce this variability, it was predicted that lows would show higher difference scores (i.e., faster in the dual-task condition) between single- and dual-task conditions [regardless of condition order] than highs.

Hypothesis 4. Consistent with past research, it was predicted that men would perform the mental rotation task faster and more accurately than women. However, as Kail et al. (1979) have found, women should be more variable in performance than men.

Method

For ease of presentation, the method and results for the preliminary screening battery and for the experiment have been separated into two sections.

Part 1: Preliminary Screening

Method

Subjects.

For the initial screening, 133 undergraduates at Virginia Tech took a 1 hour visuospatial test battery (described below); of this sample 55 were men and 78 were

women, and 11 were left-handed. The average age was 19.8 years (*SD* = 1.97). Average number of years in college was 2.4 years (*SD* = 1.3). From this sample, two subjects (1 man, 1 woman) were rejected because they had participated in the pilot study, and two (1 man, 1 woman) were rejected for extremely low scores on a test (3 SDs below the mean) because they apparently did not understand the instructions. Subjects were split by gender and, then, rank-ordered according to combined z-scores on the three visuospatial tests (described below). The top 15 and bottom 15 subjects for each gender (total *N* = 60) were invited back for the experiment. Tables 1 and 2 below present mean scores and ranges, respectively, for subjects. Subjects volunteered for the screening, and received one hour of course extra credit for their participation.

Materials.

The screening battery consisted of three pencil and paper visuospatial tests: the Minnesota Paper Form Board Test (MPFBT; Likert & Quasha, 1941) to measure the visualization factor; and the Mental Rotation Test (MRT; Vandenberg, 1978) and the Card Rotations Test (CRT; Ekstrom et al., 1976) to measure 3-dimensional and 2-dimensional speeded rotation, respectively. The WAIS Digit Span Test (Weschler, 1955) was given to determine the average digit span for the concurrent task, as in Kail (1991).

Additionally, subjects signed a release form to allow the experimenter to obtain QCA and SAT scores from the university registrar (Appendix B), a questionnaire to determine strategy for the preceding visuospatial tests (Appendix C), and a questionnaire to assess subject demographics (Appendix B).

The Digit Span Test was group administered via an audiotape recording of digits spoken at a rate of 1 digit per second, with a 10 second pause following the last digit of each series to allow the subject time to write down the digits in their proper order on the answer sheet. Subjects were instructed not to begin writing until after the last digit was spoken. The test had 7 pairs of digit sequences, increasing in length from 3 digits long to 9 digits long. Subjects were scored on both total correct (out of 14 items), as well as Digit span, which was defined as the largest set of digits for which subjects recalled both sequences perfectly (from 3 to 9).

The strategy questionnaire (Appendix C) asked subjects to describe their strategy for solving the problems on the three visuospatial tests. Additionally, subjects were asked to indicate their strategy according to two forced-choice scales: one which compares *holistic* and *detail* strategy, and another that replicates Schultz's (1991) breakdown of *moving self*, *moving object*, and *key feature* strategies

(corresponding to perspective change, speeded rotation, and analytic processes, respectively).

Procedure.

The screening battery was administered to groups of subjects over nine sessions, 1 to 2 weeks prior to the start of the individual experimental sessions. The tests were presented in the following order: demographic questionnaire, CRT (Part 2 only), MRT (Parts 1 and 2), Digit Span, MPFBT, and strategy questionnaire. The tests were timed; the CRT (80 items) took 3 minutes, the MRT (20 items each part) took 3 minutes for each part, and the MPFBT (64 items) took 20 minutes. Scores on these tests were corrected for guessing in accordance with standard scoring procedures.

Results

Mean scores on the screening battery are reported in Table 1 below. Scores are broken down by visuospatial skill/gender condition for those who participated in the experimental task, and by gender and total for all subjects who were screened. Table 2 shows the raw and z-score ranges on each test for these groups.

Table 1. *Mean Scores on the Screening Battery Tests*

GROUP	*N*	CRT *M= SD=*	MRT *M= SD=*	MPFBT *M= SD=*	DF *M= SD=*	DS *M= SD=*
Prescreened Subjects:						
Men	55	57.3(14.4)	24.5(9.1)	47.4 (9.7)	10 (2.0)	6.3(1.3)
Women	78	53.5(13.0)	17.1(5.9)	46.1(10.3)	9.4(1.7)	6.0(1.6)
Total	133	54.9(13.8)	20.2(8.2)	46.6(10.0)	9.6(1.9)	6.1(1.5)
Experimental Subjects:						
Men: Highs	13	67.2(8.4)	34.5(3.1)	54.8 (5.2)	10.5(1.8)	6.5(1.4)
Lows	12	44.0(11.8)	14.9(6.7)	39.4 (9.2)	9.5(2.2)	6.0(1.3)
Women: Highs	14	68.2(8.2)	23.6(5.5)	55.3 (5.1)	10.0(1.6)	6.0(1.2)
Lows	13	41.9(8.1)	11.0(4.6)	35.1 (9.8)	8.5(1.6)	5.7(0.9)

Note: CRT= Card Rotations Test, MRT= Mental Rotation Test, MPFBT= Minn. Paper Form Board Test, DF= Digits Forward (WAIS), DS= Digit Span

Table 2. *Raw and Z-score Ranges on the Screening Tests*

GROUP	N	CRT High(z)/Low(z)	MRT High(z)/Low(z)	MPFBT High(z)/Low(z)	COMBINED z-range
Prescreened Subjects:					
Men:	55	80(1.6)/24(-2.3)	38(1.5)/-1(-2.8)	63(1.6)/17(-3.1)	4.6/-5.0
Women:	78	79(2.0)/24(-2.3)	31(2.3)/ 4(-2.2)	62(1.5)/20(-2.6)	4.6/-5.0
Total:	133	80(1.8)/24(-2.3)	38(2.2)/-1(-2.6)	63(1.6)/17(-3.1)	5.5/-5.0
Experimental Subjects:					
Men:					
Highs:	13	80(1.6)/53(-0.3)	38(1.5)/29(0.5)	63(1.6)/46(-0.2)	4.6/ 1.6
Lows:	12	62(0.3)/24(-2.3)	26(-.2)/-1(-2.8)	50(0.3)/17(-3.1)	-0.6/-5.0
Women:					
Highs:	14	79(2.0)/53(-.04)	31(2.3)/14(-0.5)	62(1.5)/43(-0.3)	4.6/ 1.7
Lows:	13	62(0.7)/24(-2.3)	17(-.01)/4(-2.2)	56(1.0)/20(-2.6)	-2.0/-5.0

Note 1: CRT= Card Rotations Test, MRT= Mental Rotation Test, MPFBT= Minnesota Paper Form Board Test

Note 2: z-scores were computed within each gender, and for total sample.

Intercorrelations among tests in the screening battery are shown in Table 3 below. Verbal and Spatial Self-Report refer to questions which asked the subjects to rate themselves on a 9-point scale as to their overall verbal and visuospatial ability (see Appendix B). Correlations show that subjects were fairly accurate in their self-ratings in

relation to their performance on the pencil and paper tests. The three visuospatial tests were fairly intercorrelated also, similar to findings in the pilot study (i.e., CRT & MRT: $r = .61$, CRT & MPFB: $r = .48$, MRT & MPFBT: $r = .59$; from Daly & Crawford, 1993, $N = 55$, $p < .01$).

Table 3. *Intercorrelations for Screening Battery*

	VSR	SSR	CRT	MRT	MPFB	DF
Spatial Self-Report	.31*					
Card Rotations	-.21	.34*				
Mental Rotations	.03	.46**	.56**			
Minn Paper Form Board	.01	.58**	.71**	.55**		
Digits Forward	.08	.20	.25	.40**	.29*	
Digit Span	.19	.05	.02	.31*	.07	.81**

* p<.05 ** p<.01 (2 tailed)

Note: VSR= Verbal Self-Report, SSR= Spatial Self-Report, CRT= Card Rotations Test, MRT= Mental Rotation Test, MPFBT= Minnesota Paper Form Board Test, DF= Digits Forward (WAIS)

Part 2: Experimental Trials

Method

Subjects.

There were 52 subjects (27 high- and 25 low-visuospatial; 25 men and 27 women) who participated in the

experimental trials. Due to inclement weather (ice storms) and power outages, eight subjects were unable to participate. Age and year in college for the selected samples did not differ from the total.

Subjects were right-handed except for four: one ambidextrous in each skill level for the men (both preferred to use their right hand in the computer task) and one left-handed in each skill level for the women. Subjects had normal or corrected normal vision. Four subjects reported neurological or medical problems (2 concussions, 1 migraine, 1 history of epileptic seizure in infancy), but there was no performance deficit for these subjects (all were in the high visuospatial category). Subjects received one hour of course extra credit for participation in the experiment.

Materials.

Computer. The mental rotations task was administered on an IBM-compatible 386-40 MHz personal computer and displayed on a 14" VGA .28mm dot pitch non-interlaced color monitor using a Quadtel TVGA-8900C video board. The display resolution was 640x480 lines with a refresh rate of 60Hz and 8x16 dot character size. The mental rotation task was adapted from the Micro-Experimental Laboratory (MEL; Schneider, 1988) program ROTATE, which was adapted from Cooper (1975). Three programs were developed, one for each block of the experiment (Block 1+2: practice trials and

familiarization block; Block 3: single-task trials; Block 4: dual-task trials). The MEL subject scheduler program was used to automate counterbalanced block presentation. All data collection was done automatically by the computer program and stored on the hard disk.

For each trial, two figures were presented successively and the subject was instructed to determine if the second figure was a match ("same") or mirror-reversal ("different") of the first, recording their response by pressing the "1" or "2" key, respectively, on the keypad (see Appendix D for task instructions). A Fujitsu IBM-enhanced type keyboard was used; average delay for both the "1" and "2" keypad keys was 13 ms, as reported by the MEL SCANTIME routine.

Stimuli. Stimuli were two-dimensional irregular 12-point polygons (Attneave-type) used by Cooper (1975), white on a black background, presented centrally on the screen inside a white circular outline (see Figure 2). Figures measured 5 cm high and 4 cm wide on the screen within a 10 cm circumference circle. Subjects were seated 60 cm from the screen, at which point the figures subtended a visual angle of 4.77 degrees. The second test figure was rotated in the picture-plane either 0, 60, 120, 180, 240, or 300 degrees relative to the first. At each angle, half the shapes were identical and half were mirror-reversed images of the first shape. The first shape was "left-facing" half

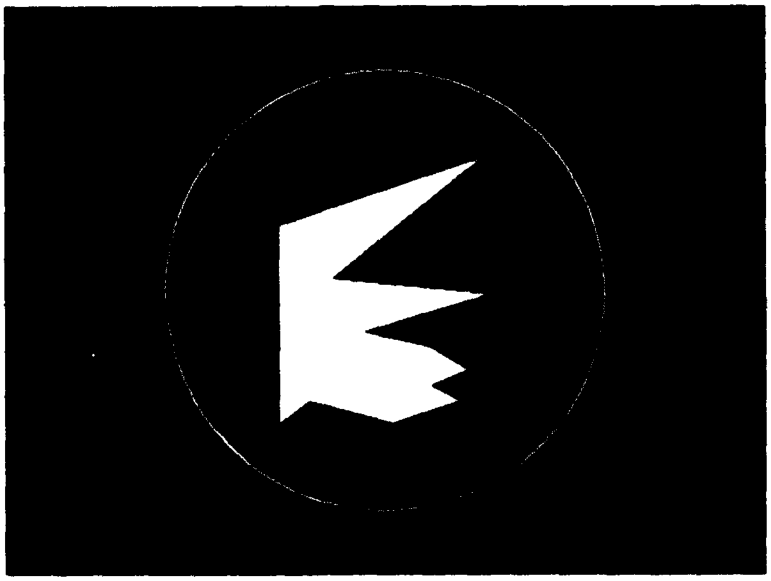

Figure 2. *Example of Stimulus Used in the Experiment*

of the time, and "right-facing" half of the time. Thus, there were 24 possible combinations [first figure orientation (2) x test figure congruency (2) x angle (6)]. Each combination was replicated four times for a total of 96 trials per block. All manipulations were counterbalanced across trials, with the same angle or response not appearing in more than three sequential trials.

Trials. Each trial began with an orientation screen presented for 0.75 seconds to prepare the subject for the trial (see Appendix D for a description of screens displayed on the computer task). Next, the first figure was presented for 2 seconds, after which the screen was blacked out and immediately the test figure was presented. At the point of

response, the test screen was removed and a feedback screen was presented for 1 s, consisting of trial response accuracy ("Correct Response!" or "Incorrect Response!"), as well as response time (in seconds) and percent correct for correct trials, and a 400ms-long tone for incorrect trials. For each block, 96 trials were presented successively in this manner.

Subjects were also given pauses within the block. For the single-task blocks, a subject-terminated pause screen appeared every 20 trials, with a check on the subject's mean accuracy and a reminder to try to improve accuracy to 90% if the subject was below 90%, or to "Keep it up!" if the subject's accuracy was 90% or higher. No pauses were built into the dual-task trials, since subjects had an opportunity to pause after they had entered the digits (see below). Following the last trial of each block, a table and graph of reaction times and percent correct at each angle was presented automatically to the subject.

Concurrent Task. For the dual-task block, subjects were asked to perform a concurrent articulatory suppression task, adapted from Baddeley and Hitch (1974), at the same time they were doing the mental rotation trials. Following the computer-displayed instructions for the block (see Appendix D), a set of six random digits (as determined by the mean WAIS digit span) was displayed on the computer

screen to subjects, who were instructed to repeat them over and over aloud to themselves as they were doing the figure comparison trials. The repeating aloud was necessary to ensure all subjects used a verbal digit-rehearsal strategy. The experimenter was present to verify this. After every six trials the subject was asked to type in the digits, in exact order, using the keyboard, after which feedback on accuracy ("Correct Response!" or "Incorrect Response!") was displayed on the computer screen and a new series of digits was presented, for a total of 96 trials (16 digit trials). Random sequences of digits were generated, as in Kail (1991), with the constraints that digits appeared only once in a sequence, and three or more digits in ascending or descending order (e.g., 1-2-3) were not allowed. Sixteen 6-digit sequences were constructed. The computer program randomly selected the order of digit sequences for each subject.

Procedure.

The computer task was administered to each subject individually, and each session lasted for about 1 hour. Instructions were presented to the subjects on the screen (see Appendix D) with the experimenter present to clarify the instructions and answer any questions. For the first block, subjects began with a practice set of 10 trials, which was repeated until a criterion accuracy of 80% correct

for the set was reached. Next, subjects were given a familiarization block of 96 normal trials, as described above. Order of the next two blocks (i.e., single- and dual-task conditions) was counterbalanced within each visuospatial skill/gender group.

Subjects were given a 5-minute rest break between blocks. Each block took about 15 minutes to perform. Although subjects performed over 300 of the same trials in the hour, most reported that they enjoyed the experiment. Subjects were encouraged to think of it as game, and to try to better their speed and accuracy with each trial. After the final block, subjects were given a strategy questionnaire and debriefed on the purposes of the experiment.

The standard procedure in mental rotation experiments, as well as other chronometric studies, is to remove outliers and incorrect responses from the data set. Response times for these trials may reflect processes other than those under investigation, such as missing the proper key or using too light a keystroke (both instances were reported by some subjects in the present study). Also, as reaction time can be defined as "the minimum amount of time needed by the subject in order to produce a correct response" (Pachella, 1974; p. 44), error trials may be justifiably removed.

Results

Practice Blocks.

To assess whether low and high visuospatial subjects, as well as men and women, differed in the number of practice trials it took to reach criterion, a 2 (Skill) x 2 (Gender) analysis of variance (ANOVA) was performed on number of practice blocks (See Table 1, Appendix F). Low visuospatial subjects needed significantly more practice blocks (M = 3.08, SD = 2.68) than did highs (M = 1.37, SD = 0.63) to meet the 80% accuracy criterion $F(1,48) = 11.22$, $p = .002$. The main effect of gender was not significant, but there was a significant interaction between skill and gender ($F(1,48) = 4.15$, $p = .047$). With the women, lows had more practice blocks (of 10 trials each) than highs (M = 3.92 blocks v. 1.21), $t(25) = 3.02$, $p = .006$. However, male lows (M = 2.17, SD = 1.34) were not significantly different from male highs (M = 1.54, SD = 0.78). Furthermore, there was a difference in variance within the female subjects (lows: SD = 3.33, highs: SD = 1.21; $F(13,14) = 61.09$, $p < .001$) but not within the male subjects. There were no differences in number of practice blocks between female lows and male lows, or between female highs and male highs.

Outliers.

Outliers were defined as response times greater than twice the mean of the respective cell (as in Kail, 1991;

Kail & Park, 1990). Overall, 0.71% (106 of 14,976 trials) of the data were removed using this criterion. A repeated measures multivariate analysis of variance (MANOVA) on number of outliers at each angle was performed to see if there were any trends. When all three blocks were included, there were main effects of skill ($F(1,288) = 4.11$, $p = .044$) and angle ($F(5,284) = 3.50$, $p = .004$), but when the initial familiarization block was excluded only the effect of angle ($F(5,188) = 3.86$, $p = .002$) remained significant. This supports the contention that the familiarization block successfully reduced task learning effects and reduced order effects in the present study, something that may have been a confound in prior research.

A Tukey HSD test revealed that mean outliers differed between angle 300° and angles 120-240° (*M*s = 0.099 outliers v. 0.029-0.045). Examination of the raw data revealed that many of the outliers at angle 300° were very close to the cutoff and would have stayed in if the cutoff were raised to 2.5 times the cell mean; but due to the low number of points removed, the original exclusion rule was maintained.

Digit Recall.

Accuracy on the concurrent digit-repeating task was examined to determine if there were any task tradeoffs. Most of the subjects ($n = 28$) answered all the digit trials correctly; there was a 5% error rate overall (42 errors out

of 832 trials). There was no difference between the two skill groups ($t(50) = 1.87$, $p = .068$), nor between men and women ($t(50) = .65$, $p = .518$) in number of correct digit-recall trials. There were no significant correlations between accuracy on the digit trials and mean response time at each angle. These findings suggest that subjects did not tradeoff performance between the two tasks. Corballis (1986) and Kail (1991) also found no effect of digit recall on mental rotation task performance.

Response Time (RT).

After outliers and error trials were removed, 13,089 observations remained. As with the error analysis (see below), the first familiarization block of trials was not analyzed. The fact that the effect of condition was significant when all three blocks were included but not between the last two blocks supports the finding, as with errors, that subjects reached asymptotes following the familiarization block. Also, the counterbalancing of block order had no effect on reaction times.

It is also customary for mental rotation studies to separate "different" trials from the analysis, since they may elicit multiple strategies in the subjects and are less revealing of processes under investigation (Cohen & Kubovy, 1993). A one-way ANOVA on response time found the main effect of object congruency (same/different) to be

significant, $F(1,13087) = 443.59$, $p < .001$. Subjects were faster on "same" trials than on "different" trials (M = 931.58 ms v. 1108.60), consistent with prior research (e.g., Cohen & Kubovy, 1993; Cooper, 1975). The aggregation of "same" and "different" trials may cloud interpretation of the data; for example, the main effect of condition (single- v. dual-task) was significant using both congruency trials ($F(1,8883) = 4.41$, $p = .036$), but not when only "same" trials were analyzed. Subsequent analyses were run using only "same" trials.

Condition, Skill, & Gender Effects on RT. Graphs of response time by angle of rotation for each Skill x Gender group for the single-task and dual-task conditions are presented below in Figures 3 and 4, respectively. A 2(Condition) nested within 2(Skill) x 2(Gender) repeated-measures multivariate analysis of variance (MANOVA), using mean RT at each of the six angles as the dependent variables (see Table 2, Appendix F), revealed significant effects for gender, $F(1,95) = 30.54$, $p < .001$, and visuospatial skill, $F(1,95) = 42.77$, $p < .001$. Men were faster than women (M = 796.65 and 974.67 ms, respectively), and high visuospatial subjects were faster than low (M = 789.98 and 1004.26 ms, respectively). There was a significant interaction between visuospatial skill and gender, $F(1,95) = 9.50$, $p = .003$. T-tests showed that men were faster than women at both high

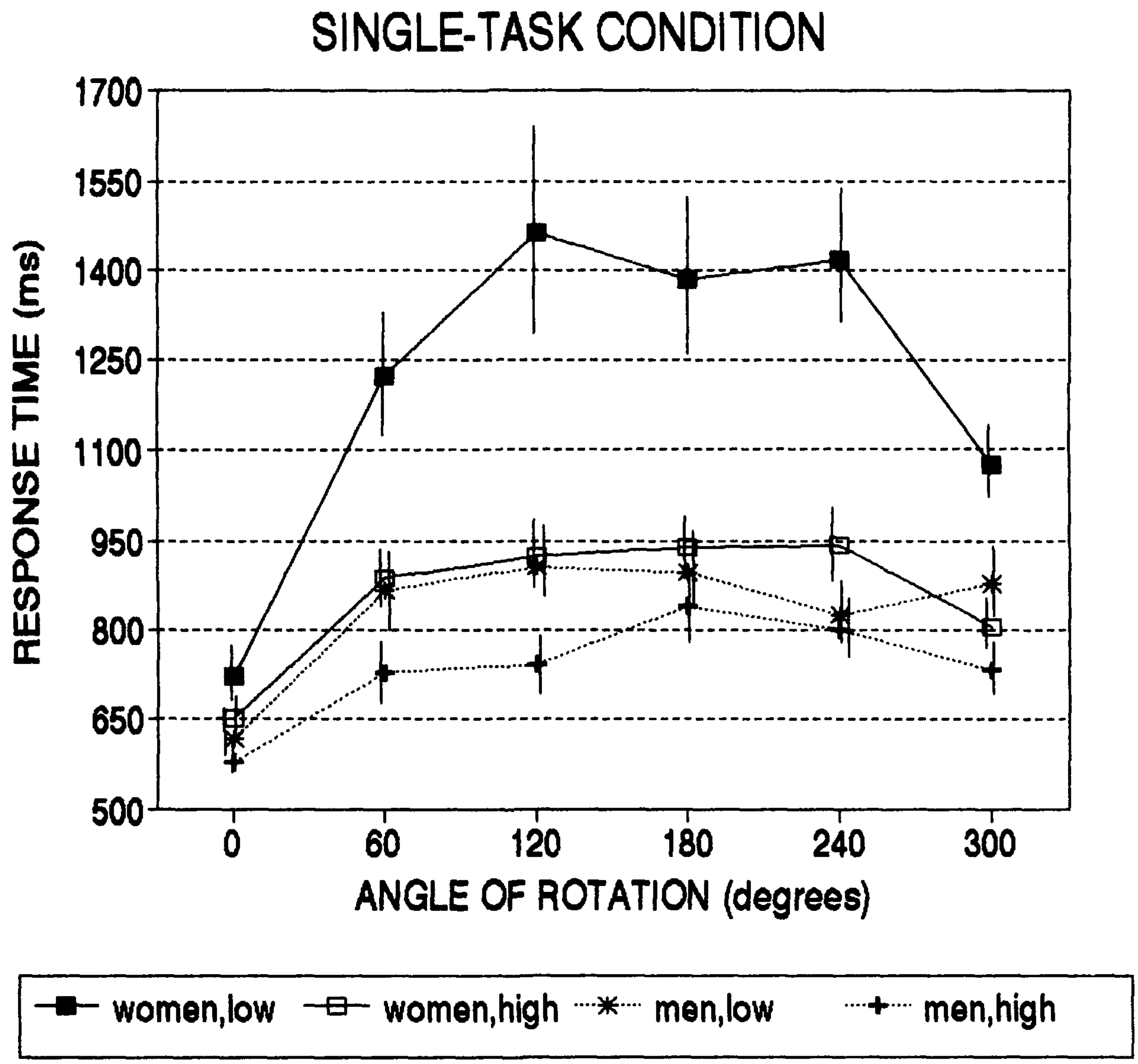

Figure 3. Response times by angular orientation for single-task condition. (Error bars show ± 1 standard error of the mean.)

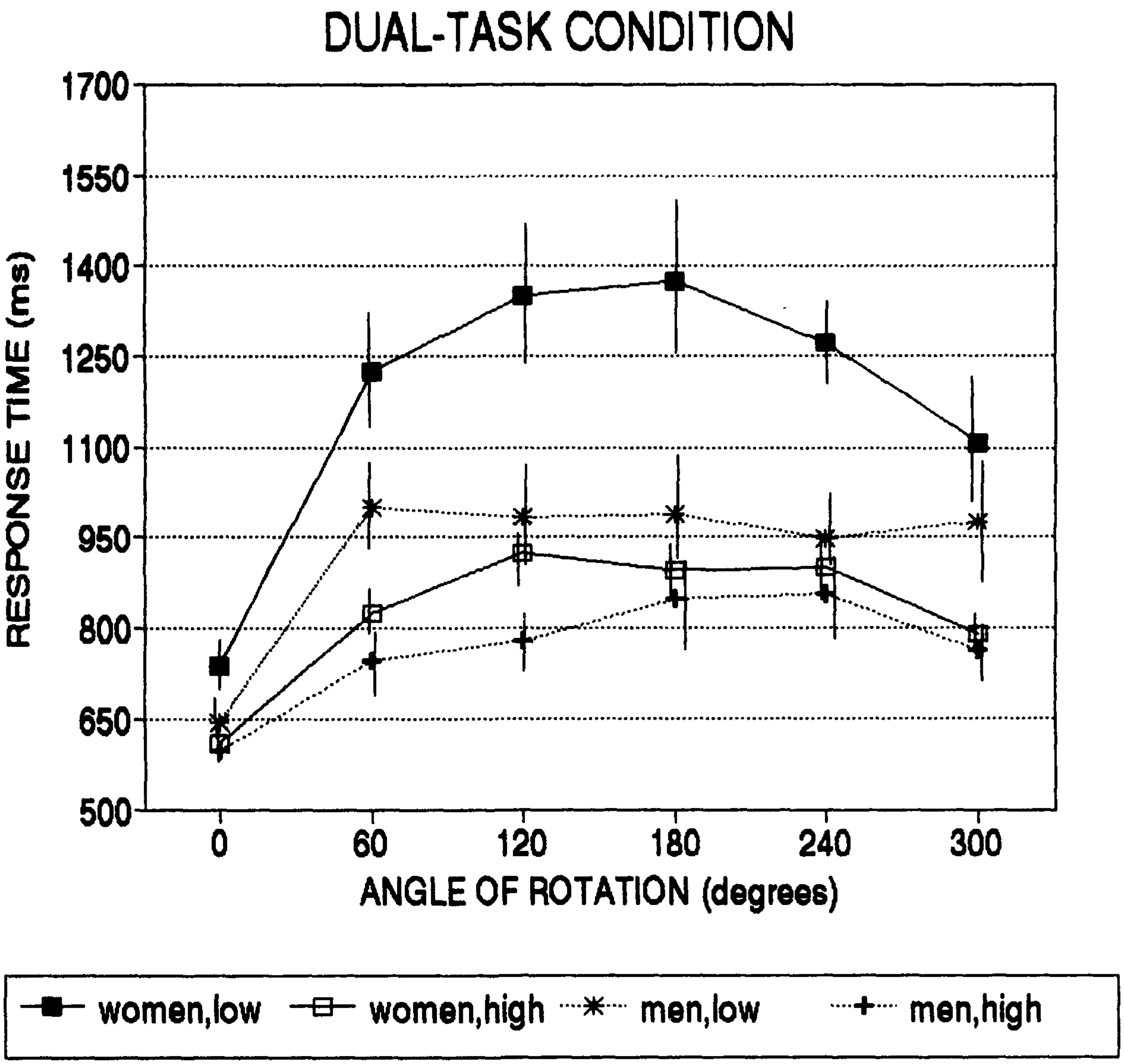

Figure 4. Response times by angular orientation for dual-task condition. (Error bars show ± 1 standard error of the mean.)

and low skill levels (lows: M = 860.89 v. 1150.89 ms; $t(1966) = 13.11$, $p < .001$; highs: M = 742.12 v. 835.50; $t(2402) = 7.96$, $p < .001$). Also, highs were faster than lows within each gender group (women: M = 835.50 v. 1150.89, $t(2203) = 16.15$, $p < .001$; men: M = 742.12 v. 860.89, $t(2165) = 8.73$, $p < .001$).

Central to the present study, the effect of task condition on RT was not significant, $F(4,95) = 0.5$, $p = .733$; that is, subjects had the same response time even when they had a concurrent dual-task. There were no significant interactions involving condition. These results conflict with those of Corballis (1986) and Kail (1991), both of whom found that mean response time was significantly longer in the dual-task condition than in the single-task.

Variability in RT. The standard deviations of the groups showed interesting patterns. There was no difference in overall RT standard deviations between the single- and dual-task conditions, $F(2184,2188) = 1.02$, $p = .592$. Women (SD = 481.41 ms) were more variable in response time than men (SD = 320.91 ms), $F(2205,2167) = 2.25$, $p < .001$. Low visuospatial subjects (SD = 511.65 ms) also showed more variability than high (SD = 291.27 ms), $F(1968,2404) = 3.09$, $p < .001$. Within each gender, lows are more variable than highs; for the women, $F(973,1232) = 4.35$, $p < .001$ (SDs = 603.28 ms v. 289.19) and for the men, $F(955,1172) = 1.48$, p

$< .001$ (*SDs* = 347.16 ms v. 285.84). However, when men and women are compared within each skill level, a different pattern emerges: only in the low-skill group are women (*SD* = 603.28 ms) more variable than men (*SD* = 347.16 ms), $F(973,995) = 3.02$, $p < .001$; male and female highs were practically equal in terms of standard deviation (*SDs* = 285.84 and 289.19 ms, respectively), $F(1232,1172) = 1.02$, $p = .687$.

Angle Effects on RT. The multivariate Hoetellings F test was used to test the significance of the repeated measure effects of angle, since the sphericity assumption was not met. There was a significant effect of angular disparity, Hoetelling's $F(5,91) = 61.89$, $p < .001$. A Tukey HSD multiple range test ($p < .05$) on the means found: RT at angle 0° was faster than for 60 to 300°; RT at 300° was faster than for 120 to 240°; and RT at 60° was faster than at 180° (respective means [0-300°]: 645, 920, 976, 988, 967, and 863 ms). There were also significant interactions of Gender x Angle, Hoetelling's $F(5,91) = 4.13$, $p = .002$, and Skill x Angle, Hoetelling's $F(5,91) = 6.71$, $p < .001$. Men were faster than women at all angles ($p < .05$), and highs were faster than lows at all angles ($p < .01$). Tukey HSD tests ($p < .05$) on mean RTs for each angle showed that for women, RT at 0° was significantly faster than for 60 to 300°, RT at 300° was faster than at 60 to 240°, and RT at 60°

was faster than at 120°. For men, the only significant difference in RT was between angle 0° and angles 60 to 300°. For the low visuospatial skill group, RT at 0° was significantly faster than for 60 to 300°, and RT at 300° was faster than at 120 & 180°. For the highs, RT at 0° was also faster than at 60 to 300°, RT at 300° was faster than at 120 to 240°, and RT at 60° faster than RT at 180° and 240°.

RT Difference Scores. As in the pilot study (Daly & Crawford, 1993) individual subject's difference scores were calculated for each angle by subtracting RT in the dual-task block from the RT in the single-task block, to determine if there was a performance effect between blocks. A 2(Gender) x 2(Skill) repeated-measures MANOVA on difference scores per angle was used to analyze these data (see Table 3, Appendix F). The only significant effect was that of gender; on average, women's difference scores indicated that they were faster in the dual-task block, while men were faster in the single-task block (mean difference for women = +27.7 ms, indicating slower RT in the dual-task block; for men $M = -57$ ms, indicating they were faster in the single-task block: $t(50) = 2.11$, $p = .04$).

Slopes.

Simple linear regression of angular disparity (0 to 180°) on response time rendered slopes and intercepts for each condition, for both same and different responses.

Slopes of the regression are said to reflect the rate of mental rotation, whereas intercepts correspond to time to encode a stimulus, compare it to the representation in memory, and respond (Cooper & Shepard, 1973). Regression functions for each block, overall and split by object congruency, are shown in Table 4 below.

Table 4. *Regression Functions for each Block, by Congruency*

Familiarization Block:	
all trials:	RT = 1044.97 ms + 0.52 x Angle
"same" trials:	RT = 928.64 ms + 0.68 x Angle
"different" :	RT = 1163.42 ms + 0.32 x Angle
Single-Task Condition:	
all trials:	RT = 907.29 ms + 0.53 x Angle
same:	RT = 788.24 ms + 0.65 x Angle
different:	RT = 1025.16 ms + 0.39 x Angle
Dual-Task Condition:	
all trials:	RT = 889.08 ms + 0.51 x Angle
same:	RT = 795.63 ms + 0.65 x Angle
different:	RT = 982.39 ms + 0.37 x Angle

Again, because of the difference in congruency, individual subject's slopes and intercepts were calculated for each condition by regressing angle (0-180°) on response

time for "same" trials. These data were then analyzed by 2(Gender) x 2(Skill) ANOVAs (see Tables 4a - 4d, Appendix F). There were main effects of gender for single-task slope, $F(1,48) = 8.34$, $p = .006$; single-task intercept, $F(1,48) = 9.36$, $p = .004$; dual-task slope, $F(1,48) = 5.78$, $p = .020$; but not for dual-task intercept. Women had larger slopes and intercepts than men (see Table 5). However, paired t-tests found no significant differences between the two conditions in either slope or intercept overall, by gender, or by skill.

Table 5. *Comparisons of Slopes and Intercepts by Gender*

	Gender		Significance	
	Men	Women	$t(50) =$	$p =$
Slopes (ms/degree):				
Single-task	1.42	2.81	2.50	.016
Dual-task	1.52	2.59	2.16	.036
Intercepts (ms):				
Single-task	639.70	760.98	2.93	.005
Dual-task	675.80	746.56	1.66	.103

The effect of visuospatial skill was significant for all dependent variables: single-task slope, $F(1,48) = 7.88$,

p = .007; single-task intercept, *F*(1,48) = 5.93, *p* = .019; dual-task slope, *F*(1,48) = 7.66, *p* = .008; and dual-task intercept, *F*(1,48) = 13.80, *p* = .001. Low visuospatial subjects had higher slopes and intercepts than high in both single- and dual-task conditions.

The only significant interaction was for single-task slope, *F*(1,48) = 6.05, *p* = .018 (see Table 4a, Appendix F). For women, low visuospatial subjects had a steeper slope than high (*M* = 4.16 ms/degree and 1.55, respectively), while there were no differences between male lows (*M* = 1.51) and highs (*M* = 1.34). In the low visuospatial skill category, women had steeper slopes than men (*M* = 4.16 v. 1.51) while there was no difference between men and women with high visuospatial skill.

Variability in Slopes and Intercepts. As for the response time analysis, differences in group variability were examined. There was a significant difference between men (*SD* = 1.24 ms/degree) and women (*SD* = 2.50 ms/degree) only for the single-task slope, *F*(27,25) = 4.04, *p* = .001. Since there was no difference in the dual-task slope, this would suggest that the concurrent task succeeded in reducing the variability in mental rotation rate for the women. Low visuospatial subjects were more variable than high for both condition slopes and the dual-task intercept (*p* = .002).

Again, there were different patterns when gender was

broken down by visuospatial skill For women, lows were more variable than highs for all but single-task intercept ($p < .05$), but there were no differences in variance between highs and lows for men. Within each visuospatial skill level, the only significant difference was between female lows (SD = 2.87 ms/degree) and male lows (SD = 1.28 ms/degree) in the single-task slope, $F(13,12) = 5.04$, $p = .012$. Together with the previous result, this would suggest that the concurrent task decreased the rotation rate variability within the female low visuospatial skill group.

Errors.

Overall experiment-wise error rate was 11.9%. Error rates by condition are shown in Table 6. As can be seen, inclusion of the initial familiarization block may have helped to decrease errors due to learning the task. This

Table 6. *Error Rates by Condition*

Block 1 (practice trials)	337/ 1140 = .296
Block 2 (familiarization)	757/ 4992 = .152
Block 3 (single-task condition)	490/ 4992 = .098
Block 4 (dual-task condition)	534/ 4992 = .107
TOTAL (all trials)	1781/14976 = .119
TOTAL (single- & dual-task)	1024/ 9884 = .103

can be seen by the fact that the effect of task condition was significant when all three blocks were included in the ANOVA, but not when the familiarization block was removed. This supports the conclusion that subjects reached asymptote prior to beginning the task manipulation trials. As with the previous analyses, trials from the familiarization block were excluded from the analysis.

Number of errors can serve as an estimate of trial difficulty (Lohman, 1988) in the same sense as increased response time for greater angular discrepancy. This relationship can be seen by the significantly positive correlation between number of errors and mean response time (overall $r = .314$, $p < .01$; see Table 7 below). That is,

Table 7. *Correlations between Mean Response Time and Number of Errors by Angle of Rotation*

ANGLE	r
0°	.419**
60°	.143*
120°	.384**
180°	.346**
240°	.222**
300°	.194**
Overall	.314**

$N = 1870$; * = $p <$ .05 ** = $p <$ .01 (2-tailed)

for trials with longer response times, there were more errors.

A one-way ANOVA of task condition on mean number of errors revealed that the effect of task condition was not significant, $F(1,1246) = .86$, $p = .354$. As with the data from response times, slopes, and intercepts, number of errors did not significantly differ when subjects were given a concurrent task versus when they were performing the rotation task alone.

A one-way ANOVA also found the main effect of object congruency to be significant, $F(1,1870) = 11.77$; $p < .001$. However, it is surprising since subjects made more errors on trials when the stimuli were the "same" ($M = 1.07$) versus when they were "different" ($M = 0.84$), except when the stimuli were in identical orientations (i.e., 0° difference): M for "same" = 0.08, M for "different" = 0.55; $t(310) = 5.02$, $p < .001$. Since subjects were faster on "same" trials than "different", as is the case in most mental rotation studies, this may reflect a speed-accuracy tradeoff for "same" stimuli. That is, some subjects reported knowing the right answer but pressing the wrong button in some instances. These results are inconsistent with the overall correlations of response time with errors reported above, yet they support Pachella's (1974) statement about the inverse relationship between error rate and

latency.

Also consistent with the RT analysis, there were conflicting results when both types of congruency trials (same or different) were included in the analysis. When ANOVAs were run using trials of both congruency types, there was a main effect of condition order ($F(1,1152) = 15.56$, $p < .001$); but this effect, as well as any interactions with it, was nonsignificant when only the "same" trials were analyzed ($F(1,576) = 2.72$, $p = .100$). Consistent with the previous analyses, the following ANOVAs were run using only "same" trials.

Skill and Gender. Number of errors was analyzed by a 2(Order) x 2(Skill) x 2(Gender) x 6(Angle) ANOVA (see Table 5, Appendix F). There was a significant main effect of visuospatial skill, $F(1,576) = 68.45$, $p < .001$. Lows made more errors than highs overall ($M = 1.36$ errors v. 0.53). There was also a significant Skill x Angle interaction, $F(5,576) = 3.39$, $p = .005$. These results are not noteworthy, yet they support the study's categorizations of skill based on the paper and pencil tests. The main effect of gender was also significant, $F(1,576) = 17.57$, $p < .001$; overall, women made more errors than did men, Ms = 1.12 and 0.72, respectively. This is consistent with the response time results, as well as past reports of gender differences in visuospatial skill. However, there was also an

interaction of Skill x Gender ($F(1,576) = 4.50$; $p = .034$); women made significantly more errors than did men only in the low visuospatial skill category ($M = 1.65$ v. 1.03).

Angle Effects. The main effect of angle was significant, $F(5,576) = 13.36$; $p < .001$. A Tukey HSD multiple range test found that error means differed only between 0° and all other angular discrepancies at the .05 level [*Ms*, respectively (0 to 300°): 0.05, 0.99, 1.11, 1.13, 1.13, 1.17]. Mean errors did not differ among angles 60° through 300°. The interaction of Angle x Gender ($F(5,576) = 2.42$, $p = .035$) was further analyzed by t-tests at each angle; women had significantly more errors than men at angle 180° only ($M = 1.67$ v. 0.64). Trials at 180° are unique in that the correct answer may be found rapidly by "flipping" the figure, accounting for faster response times at 180° and a non-linear slope. As Lohman (1988) suggests, errors and rapid performance at easily labeled orientations (such as 180°) may signal non-rotational strategies. Interestingly, female low visuospatial subjects had more errors at 180° ($M = 2.65$) than female highs ($M = .75$) and male lows ($M = .92$), while there were no differences between male lows and highs, or between female highs and male highs. This would suggest that women in the low visuospatial skill group were using different, non-rotational, strategies than the other groups.

Variability. Consistent with the preceding response time analyses, lows (SD = 1.65 errors) showed more variability in errors than highs (SD = 0.91), $F(300,324) = 3.25$, $p < .001$. Women (SD = 1.49) showed more variability than men (SD = 1.21), $F(324,300) = 1.51$, $p < .001$. Again, when women and men are compared within each visuospatial skill level, only in the low skill-level are the women more variable than men, $F(156,144) = 1.52$, $p = .012$; SDs = 1.65 and 1.04 errors, respectively.

Prescreening Battery and Task Performance Correlations.

Prescreening test scores were correlated with subject's slopes, intercepts, errors, and mean response time (RT) for the single-task and dual-task block conditions; results are shown in Table 8 below.

As Table 8 shows, although subject's visuospatial self-report rating is intercorrelated with their verbal self-report rating (subjects tended to rate themselves as high on both skills), they are differentiated in that their visuospatial self-report is related to visuospatial task performance (tests and rotation task), while their verbal rating is not. As in the pilot study, the three paper and pencil visuospatial tests were correlated with rotation task performance. The negative correlations signify that for higher scores on the tests subjects have lower slopes, intercepts, and errors (i.e., better performance). By

Table 8. *Prescreening Test Score Correlations with Performance Measures*

	VSR	SSR	CRT	MRT	MPFB	DF	DS
Slope:							
Single-task	-.04	-.28*	-.36**	-.21	-.32*	-.17	-.11
Dual-task	.08	-.16	-.37**	-.31*	-.36**	-.29*	-.19
Intercept:							
Single-task	-.11	-.28*	-.36**	-.29*	-.30*	-.12	-.02
Dual-task	-.20	-.33*	-.46**	-.33*	-.48**	-.05	.08
Errors:							
Single-task	.11	-.44**	-.51**	-.34*	-.46**	-.34*	-.21
Dual-task	.14	-.45**	-.53**	-.45**	-.55**	-.29*	-.19
Mean RT:							
Single-task	-.07	.39*	.13	.04	.31	-.01	-.04
Dual-task	-.07	.01	.30	.30	.11	-.05	-.20

* p<.05 ** p<.01 (2 tailed)

Note: VSR= Verbal Self-Report, SSR= Spatial Self-Report, CRT= Card Rotations Test, MRT= Mental Rotation Test, MPFBT= Minnesota Paper Form Board Test, DF= Digits Forward (WAIS), DS= Digit Span

contrast, positive correlations for simple mean RT would suggest that higher test scores are associated with slower response time; further, the correlations are not significant. Simple mean RTs then do not seem to be good performance measures as compared with the other measures, possibly because they do not take into account the effects of angle and congruency, (RTs for *all* trials are aggregated

in this measure).

Strategy and SAT Relationships with Performance.

Subjects gave consent to have their Scholastic Achievement Test (SAT) scores and Quality Credit Average (QCA) obtained from the university registrar. Math SAT, Verbal SAT, Total SAT, and QCA were correlated with the visuospatial tests; results are presented in Table 9.

Table 9. *Correlations of Predictor Tests with SAT, QCA*

	Math SAT	Verbal SAT	Total SAT	QCA
Card Rotations	.34*	.08	.32*	.00
Mental Rotations	.13	-.03	.24	-.06
Minn Paper Form Board	.48**	.20	.46**	.05
Digits Forward	.00	-.12	-.05	-.04
Digit Span	.12	.10	.22	-.06
Verbal Self Report	-.02	-.10	-.06	-.05
Spatial Self Report	.03	-.10	-.02	-.04

$N = 50$; $*p < .05$ $**p < .01$ (2-tailed)

Note: SAT= Scholastic Achievement Test, QCA= Quality Credit Average

Math SATs correlated significantly with two of the three visuospatial tests; Card Rotations and the Minnesota

Paper Form Board Test, but not with the Mental Rotations Test. By contrast, Verbal SAT did not correlate significantly with any of the tests. QCA also did not correlate significantly with any of the tests.

Correlations were also calculated for the task performance measures of slope, intercept, errors, and mean RT with SAT scores and QCA. Results are shown in Table 10. Again, higher Math, but not Verbal, SAT scores were correlated with faster performance (i.e., lower RT and

Table 10. *Correlations of SAT, QCA with Task Performance*

	Math SAT	Verbal SAT	Total SAT	QCA
Slope:				
Single-task	-.43**	-.03	-.28*	.14
Dual-task	-.36*	-.10	-.27	-.08
Intercept:				
Single-task	-.36**	-.24	-.35*	.42**
Dual-task	-.45**	-.30*	-.44**	.34*
Errors:				
Single-task	-.34*	-.16	-.30*	.14
Dual-task	-.42**	-.14	-.33*	.23
Mean Response Time:				
Single-task	-.52**	-.20	-.43**	.36**
Dual-task	-.52**	-.28*	-.47**	.16

$N = 50$; $*p < .05$ $**p < .01$ (2-tailed)

Note: SAT= Scholastic Achievement Test, QCA= Quality Credit Average

intercept, flatter slopes) in both the single- and dual-task conditions for the mental rotation task.

Subjects were split at the 50% cumulative frequency point into high and low Math SAT and Verbal SAT score groups, and 2(MSAT) x 2(VSAT) x 2(Gender) ANOVAs were run on slopes and intercepts. The Math SAT effects were the only significant ones; for single-task slope, $F(1,43) = 6.81$, $p = .012$, dual-task slope, $F(1,43) = 7.31$, $p = .010$, and dual-task intercept, $F(1,43) = 4.96$, $p = .031$. High scorers on Math SAT had lower single-task slopes ($M = 1.27$ ms/deg v. 3.01), dual-task slopes ($M = 1.25$ v. 2.91), and dual-task intercepts (656.69 ms v. 768.39). There was no effect of Verbal SAT score, gender, nor any interactions.

Strategy. The strategy questionnaire yielded little useful data. There were no differences between low and high visuospatial skill groups or men and women in strategy ratings. Ratings for the single-task block and the dual-task block were highly intercorrelated; this may be due to the fact that both were retrospective reports, filled out at the same time.

Paired t-tests revealed that there was a significant difference between subjects reporting the "Detail" strategy; more reported using it in the single-task condition than the dual-task condition ($M = 57\%$ v. 50%; $t(51) = 2.10$, $p = .04$). Also, there was a trend ($p < .09$) for women to report more

holistic strategies and less detail strategies in the dual-task condition than the single-task condition, whereas there were no such trends for the men. This supports the hypothesis that subjects would report more holistic strategies when given a concurrent articulatory suppression task.

Discussion

Overview of Findings

With respect to the hypotheses of the study, it was found that: 1) low visuospatial skilled subjects did have more errors, slower RTs, greater slopes, and more variability than highs; 2) subjects did not have more errors, slower response times, more variability, or flatter slopes in the dual-task condition as compared to the single-task condition; 3) lows did not show higher difference scores from the single to the dual-task block, and 4) men did perfo[illegible]e mental rotation task better than women and women were more variable in their performance than men.

General Discussion

Results of this study are consistent with results from other mental rotation studies previously mentioned. There was an effect of angle of orientation on both reaction time and error; the linear increase in reaction time with an increase in angular disparity was replicated. Rotation

times for "same" responses were faster than for "different" responses, suggesting that subjects compared the "rotated" test figure with a memory image of the standard (Cooper, 1975). The study also illustrates the wide individual differences in visuospatial ability: low visuospatial subjects had significantly more practice blocks, slower response times, larger slopes and intercepts, more errors, and also more variability in response times and errors as compared to those who scored higher on paper and pencil visuospatial skill tests.

Gender Differences.

Consistent with prior research (e.g., Bryden et al., 1990; Kail et al., 1979; Lohman, 1986), there was a gender effect on the mental rotation task favoring men. Women scored lower on the prescreening tests, had more practice blocks, slower response times, larger slopes and intercepts, and more errors than men. However, congruent with findings for those with low visuospatial ability, women are also more variable than men in terms of response times and errors. These results support Kail et al. (1979) and Halpern's (1992) contention that gender differences in visuospatial ability may be due only to group differences in variability.

Further, if you factor in individual differences in visuospatial skill, the gender differences exist only in the low category. For mental rotation slopes, intercepts, and

errors, women were equal to men in the high category and poorer than men in the low visuospatial skill category only. Also, in terms of the dual-task, women are more likely to improve performance when given the concurrent digit-repeating task, as indicated by mean difference scores in response time. Women also showed no difference in slope variability from men in the dual-task condition, whereas there was a difference in the single-task condition. These results indicate that the concurrent task may have had a beneficial effect for the women, particularly those with low visuospatial skill.

Effect of a Concurrent Task.

Overall performance did not decrease on the mental rotation task when a digit-repeating concurrent task was required, either in terms of errors, mental rotation rate (i.e., slope) or mean RT. Corballis (1986) and Kail (1991) also reported no effect of digit-recall task on slope, although both found an increase in mean RT during digit-recall. The difference in mean RT results may be due to different concurrent-task requirements; that is, the prior studies asked subjects only to recall digits, not to "repeat" them as Baddeley and Hitch (1974) required their subjects, to ensure that they were taxing the articulatory loop of working memory. As such, it cannot be determined which strategy the subjects used--some may have used a

visuospatial strategy for memorizing the digits. Interference between a visuospatial digit-recall strategy and mental rotation may lead to increased RT, but the rate of rotation (slope) may be inflexible to mental load, as Corballis (1986) and Kail (1991) suggested that mental rotation is an automatic process.

Results can also be interpreted in terms of the dual capacity theories of attention and working memory (e.g., Baddeley, 1992; Wickens, 1992). By repeating the digits, subjects were being forced to tax the auditory or phonological loop separately from the visuospatial loop; other digit-recall strategies (e.g., "seeing" the numbers) may just increase the taxing of the visuospatial loop, which may lead to overall increased response time, but should not interfere with the automatic process (i.e., rotation rate). By contrast, if subjects use separate strategies for the two tasks and involve separate mental resources, they should be able to perform the two tasks equally well. If the task does not increase overall mental load, performance should not decrease with an additional task.

Comparison of Slopes.

Comparison of slopes from the regression of response time on angular orientation shows that there were differences between the present and prior dual-task studies. Corballis (1986) reported slopes of 3.46 ms/deg for the

single-task versus 4.02 ms/deg for the digit-recall task; and Kail (1991) reported 2.38 ms/deg and 2.43 ms/deg, single- v. dual-task (for adult subjects), respectively. These compare to 0.53 ms/deg and 0.51 ms/deg, respectively, in the present study. These differences could be due to the articulatory suppression effects of the present study; however, as mentioned previously, different task conditions (e.g., different stimuli [abstract polygons v. familiar letters], angular orientations, digit recall frequency) make comparisons between mental rotation studies difficult.

A brief discussion of slopes in mental rotation studies may be in order here. Recent literature has focused on "flat slopes" as an indication of a comparison process other than mental rotation. Cohen & Kubovy (1993) suggested that simply giving the subjects pressure to reduce their response time led to flat slopes (e.g., 0.34 ms/degree, compared to 1.52 ms/degree in the "no pressure" condition). Dror (1992) found that a group of pilots had flatter slopes (-0.5 ms/degree) than another group of control subjects.

Cohen & Kubovy (1993) stated two necessary criteria for demonstration of "mental rotation": 1) a positive slope and 2) a limiting rate of rotation, which they defined as above 1 ms/degree. As such, the slopes from the present study are well below the limiting rate criterion although subjects were not under increased pressure to respond faster, nor

were they from a specially experienced population. As already mentioned, lack of standardization between experiments makes it difficult to generalize results. It is beyond the scope of the current study to argue whether "mental rotation" per se is taking place. The mental rotation task was used here as a visuospatial task on which individuals differ in their performance strategies, and for which it was hypothesized that an individual's performance would be differentially affected by a concurrent task. Whether statistical analyses support the case for "mental rotation" or not, the fact remains that most subjects, as Cooper & Shepard (1973) found, did report "rotating the object in [their] head".

Subject Reports.

Subject reports also illustrate the differential effect of strategy on performance. One high visuospatial subject reported that he had a "photographic memory" and initially tried to memorize the digits imaginally, but quickly found out that would not work with the rotation task. By contrast, two subjects reported that they had previously "voiced" in their head "right" or "left", corresponding to the direction a detail of the stimulus was facing; repeating the digits interfered with this rotation strategy, possibly forcing them to adopt a more holistic strategy for the rotation task [both subjects' slope and intercept decreased

in the dual-task condition].

A large number of subjects (*n* = 16) reported that they performed better with the concurrent task, and that they felt it was easier [a cursory review of slopes and intercepts showed that for 63% of these subjects, performance did improve]. This was interesting because nearly all the subjects were initially shocked by the instructions, and felt that they "didn't know if they would be able to do it". There were many similar comments when subjects were asked an open-ended question if they "noticed any difference in their performance on the task with the digits from when [they] did the task without". One low visuospatial subject said that his accuracy was better with the digits, maybe "due to the fact that part of my mind was distracted by the six numbers. I wasn't allowed to put as much effort into my confusing strategies." He found that "when I just concentrated on the figure and left most of my mind blank, I did better than when I tried to make up various strategies." Many other subjects (*n* = 12) reported that they were "thinking too much" or "too hard" and that it was "easier to concentrate" or "focus" on the mental rotation task when they had to repeat the digits, such as when they "voiced" "left" or "right" in their minds during the task. One low visuospatial subject reported that the digit task "took my mind off how difficult and taxing the

figure task was and as a result, my accuracy was better." Many subjects were impressed by their perceived improvement and could not report how they did the rotation task, and that they "just did it", "just looked at it" and "just knew" if the figure was same or different.

Other subject reports lend insight as to why performance did not decrease with the dual-task. One explanation could be that subjects exerted more "mental effort" on the dual task. Subjects' subjective ratings of mental effort were higher in the dual-task condition (M = 6.16 v. 6.69; $t(50) = -2.41$, $p = .02$); however, this may be due to the finding that low visuospatial subjects had higher ratings than high visuospatial subjects in both conditions ($p < .05$).

Another aspect of the digit-repeating task that may have helped performance was that subjects could keep a "rhythm" or pace to perform the trials. Many subjects reported that they got into a rhythm or kept a beat. Keeping a pace may have resulted in lowering the variability in response time, which may be supported by the fact that standard deviations were lower in the dual-task block than the single-task block.

Other subjects reported that they did better at the task because they were more practiced at it. Some subjects reported that by the end they knew the stimuli pairs and the

correct solutions. One low-spatial subject reported that she "tried to remember [her] mistakes". These responses would tend to support Kail & Park's (1990) instance-based theory of mental rotation practice effects.

Strategy Effects.

Cognitive strategy is an inferred process, and as such it is very difficult to measure precisely (if at all, some will argue). One reason more differences in strategy were not found is that the present measure of strategy was not sensitive enough to detect shifts in strategy from condition to condition or trial to trial, as has been evaluated by Lohman (1988) and Just and Carpenter (1986). The distinction between holistic and detailed processing may have been blurred also, since many subjects reported focusing on one detail and rotating that as a whole, versus rotating the entire shape. The pencil and paper questionnaire is not sensitive enough to detect subtle shifts in strategy. More objective (e.g., psychophysical) measures may be needed, such as the eye-tracking methodology used by Just and Carpenter (1986). Pupillary response could then also be used to determine if shifts in performance on the dual task can be attributed to higher arousal (for review see Schiffman, 1990).

Future Research

The present results indicate that there may be

something to the hypothesis that a concurrent task may have a differential effect on task performance, depending on individual differences in task strategy. Future research could take a psychophysical approach to measure subtle shifts in strategy. Another tack would be to replicate the present dual-task approach using an analogous verbal task in place of the mental rotation task, to determine if a visuospatial concurrent task can interfere with visuospatial strategies for performing a verbal task (as done by Logie, 1986).

With regard to gender differences, the most beneficial approach to take would be to look at within-group variability. For example, when comparing men and women on various tasks it is essential to ensure the homogeneity of variance assumption is not ignored. More sensitive measures of task strategy should be used to identify between-gender differences in strategy. For example, the Cooper (1982) and Carpenter and Just (1986) investigations of individual differences in strategy did not look at gender differences.

If performance differences in cognitive tasks are due to individual differences in strategy, the next question is whether individuals can be trained to use the more efficient strategy. Matthews, Hunt, and MacLeod (1980) found that subjects can be instructed to adopt an alternative strategy for a sentence-picture verification task, although response

times were faster for those strategies the subject spontaneously adopted than for the strategies the subject switched to. However, as suggested by the present study, it may be possible to "force" the subject to "spontaneously" (or *covertly*, as opposed to *overtly*) shift to an alternative strategy. It would also be helpful to measure individual's cognitive flexibility, to identify those who may not be able to shift strategies as well.

Conclusions

The importance of the present study lies in the finding that there are individual differences in performance on a mental rotation task, primarily indicated by the variance within groups. Gender differences in performance can, for the most part, be attributed to a larger variance within the women; it is only one subpopulation of the women that is at the lower end of the performance distribution. This variability is most likely due to differences in solution strategy, although the present methodology is not sensitive enough to demonstrate this.

The finding that subjects' performance did not decrease with a concurrent verbal task initially goes against common sense, although with respect to dual-capacity theories of information processing it is reasonable. The indication that some subjects benefitted from the concurrent task requires closer examination. The significance of this study

in terms of individual flexibility in cognitive strategy is also of interest.

Finally, "mental rotation", *per se*, is not of interest here. As with other cognitive phenomena, there are differences in methodology that make its generalizability difficult. However, it is helpful to use the task as a tool to examine individual differences in information processing. This approach may be more instrumental for understanding human cognition than simply identifying and dissecting experimental phenomena.

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Appendix A. Informed Consent Forms

Informed Consent Form

TITLE OF EXPERIMENT: Visuospatial Skills and Mental Rotation

EXPERIMENT #: 2057-94

1. PURPOSE OF EXPERIMENT.

You are invited to participate in a study about visuospatial skills.

2. PROCEDURE TO BE FOLLOWED IN THE STUDY:

To accomplish the goals of the study, you will be asked to take pencil and paper tests of cognitive and visuospatial abilities. This will take 1 hour. *You may be called back to participate in a follow-on experiment, which may take another hour.*

3. ANONYMITY OF SUBJECTS AND CONFIDENTIALITY OF THE RESULTS:

The results of this study will be kept strictly confidential. Your responses will not be seen or released to anyone other than members of the research team without your written consent. The information you provide will have your name removed and only a subject number will identify you during analyses and any write-up of the research.

4. DISCOMFORTS AND RISKS FROM PARTICIPATING IN THE STUDY:

There are no apparent risks to you from participation in this study.

5. EXPECTED BENEFITS:

This research will further understanding of the mechanisms underlying mental rotation and individual differences in visuospatial skills.

6. FREEDOM TO WITHDRAW:

You are free to withdraw from participation in this study at any time without penalty.

7. EXTRA CREDIT:

For participation in the test battery you will receive 1 hour's credit. *If you are called back for the follow-on experiment, you will receive an additional hour's credit.*

8. USE OF RESEARCH DATA:

The information from this research may be used for scientific or educational purposes. It may be presented at scientific meetings and/or published and republished in professional journals or books, or used for any other purpose which Virginia Tech's Department of Psychology considers proper in the interest of education, knowledge, or research.

9. APPROVAL OF RESEARCH:

This research project has been approved by the Human Subjects Committee of the Department of Psychology and by the Institutional Review Board of Virginia Tech.

10. SUBJECTS' PERMISSION:

1. I have read and understand the above description of the study. I have had an opportunity to ask questions and have had them all answered. I hereby acknowledge the above and give my voluntary consent for participation in this study.
2. I also understand that if I participate I may withdraw at any time without penalty.
3. I give permission to the researchers to obtain my SAT scores from the Virginia Tech Registrar. These scores will be treated confidentially as mentioned in paragraph 3 above.
4. I understand that should I have any questions about this research and its conduct, I should contact any of the following:

Primary Researcher: Paul K. Daly	phone: 951-1565
Faculty Advisor: Helen J. Crawford	phone: 231-6520
Chair, HSC: Robert J. Harvey	phone: 231-7030
Chair, IRB: Ernest Stout	phone: 231-9359

Subject's Signature: ______________________________ Date: __________

Subject's ID #: ______________________________

Informed Consent Form

TITLE OF EXPERIMENT: Visuospatial Skills and Mental Rotation
EXPERIMENT #: 2057-94

1. PURPOSE OF EXPERIMENT.

You are invited to participate in a study about visuospatial skills.

2. PROCEDURE TO BE FOLLOWED IN THE STUDY:

To accomplish the goals of the study, you will be asked to perform a computerized visuospatial task, which will take 1 hour.

3. ANONYMITY OF SUBJECTS AND CONFIDENTIALITY OF THE RESULTS:

The results of this study will be kept strictly confidential. Your responses will not be seen by or released to anyone other than members of the research team without your written consent. The information you provide will have your name removed and only a subject number will identify you during analyses and any write-up of the research.

4. DISCOMFORTS AND RISKS FROM PARTICIPATING IN THE STUDY:

There are no apparent risks to you from participation in this study.

5. EXPECTED BENEFITS:

This research will further understanding of the mechanisms underlying mental rotation and individual differences in visuospatial skills.

6. FREEDOM TO WITHDRAW:

You are free to withdraw from participation in this study at any time without penalty.

7. EXTRA CREDIT:

For participation in the this task you will receive 1 hour's credit.

8. USE OF RESEARCH DATA:

The information from this research may be used for scientific or educational purposes. It may be presented at scientific meetings and/or published and republished in professional journals or books, or used for any other purpose which Virginia Tech's Department of Psychology considers proper in the interest of education, knowledge, or research.

9. APPROVAL OF RESEARCH:

This research project has been approved by the Human Subjects Committee of the Department of Psychology and by the Institutional Review Board of Virginia Tech.

10. SUBJECTS' PERMISSION:

1. I have read and understand the above description of the study. I have had an opportunity to ask questions and have had them all answered. I hereby acknowledge the above and give my voluntary consent for participation in this study.
2. I also understand that if I participate I may withdraw at any time without penalty.
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Chair, HSC: Robert J. Harvey	phone: 231-7030
Chair, IRB: Ernest Stout	phone: 231-9359

Subject's Signature: ______________________________ Date: __________
Subject's ID #: ______________________________

Appendix B. Release Form and Subject Demographics Questionnaire

Release Form

I do hereby authorize Paul Daly and/or Dr. Helen J. Crawford to receive my Scholastic Achievement Test scores and overall QCA from my Academic Records at Virginia Tech.

NAME (please print): ______________________________

ID number (please print clearly): _____-____-_____

SIGNED: _______________________ **DATE:** _________

Participant Information

Phone #: ________________ Best time to be reached: ____________

Gender (please circle): [Male] [Female] Age: _______

Year in College (please circle): 1 2 3 4 5+ Academic Major: ___________

Are you right-handed or left-handed (please circle)?: [Right] [Left] [Both]

In comparison to other students at this university, please rate yourself as to your ***verbal*** ability (such as writing, reading, language, grammar, etc.) and ***spatial/visual*** ability (such as visualizing objects, reading diagrams, maps, pictures, drawings, etc.):

Verbal Ability:

1 -------- 2 -------- 3 -------- 4 -------- 5 --------- 6 -------- 7 -------- 8 -------- 9
Low Medium High

Spatial Ability:

1 -------- 2 -------- 3 -------- 4 -------- 5 --------- 6 -------- 7 -------- 8 -------- 9
Low Medium High

Do you have any history of neurological conditions (i.e., epilepsy, strokes, concussion, etc.)?

NO YES (please explain): ____

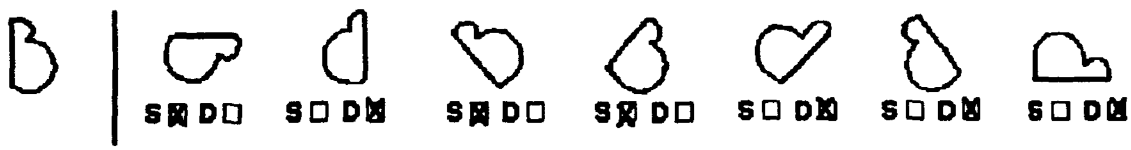
Appendix C. Preliminary Screening Battery Strategy Questionnaire

Strategies Questionnaire

We would like you to think about the methods or strategies that you used to solve the problems you have been working on. Below are examples of the types of problems and space for you to describe the method or strategy you used to solve theses problems. If you used more than one method, then please indicate the degree to which you used each method.

The CARD ROTATIONS TEST required that you determine if figures were same as or different from a particular figure.

Directions: Mark the box beside the S if it is the same as the one at the beginning of the row, or mark the box beside the D if it is different from the one at the beginning of the row.



For this test, what method(s) or strategies did you attempt? Describe each. How did you determine whether figures were the same or different?

Which strategy (method) seemed to be most successful for you?

There are individual differences in how we think. Some people think with words and others think with images (pictures of things in their "mind's eye"). Think back to taking this test, and circle the best description given below:

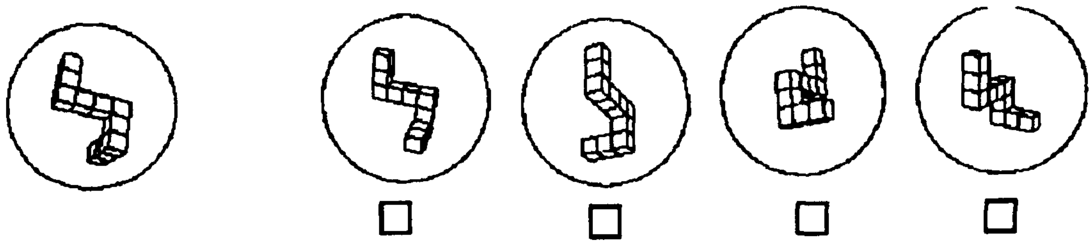
When you were comparing the comparison and test figures, overall to what degree could you "see in your mind's eye" the specific figure?

1	2	3	4	5	6	7
Never	Once in a while	Somewhat	Half & Half	More so	Pretty much	Always

PLEASE COMPLETE THIS PAGE BEFORE GOING ON AND DO NOT TURN BACK

On the MENTAL ROTATIONS TEST you were given a specific comparison figure and asked to determine which of the accompanying test figures were identical to the comparison figure.

Directions: Put an X in the box under the test figures that are the same as the comparison figure.



For this test, what method(s) or strategies did you attempt? Describe each. How did you determine whether figures were the same or different?

Which strategy (method) seemed to be most successful for you?

There are individual differences in how we think. Some people think with words and others *think with images* (pictures of things in their "mind's eye"). Think back to taking this test, and circle the best description given below:

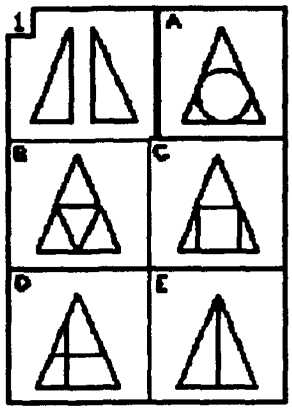
When you were comparing the comparison and test figures, overall to what degree could you "see in your mind's eye" the specific figure?

1	2	3	4	5	6	7
Never	Once in a while	Somewhat	Half & Half	More so	Pretty much	Always

PLEASE COMPLETE THIS PAGE BEFORE GOING ON AND DO NOT TURN BACK

The PAPER FORMBOARD TEST required that you determine what a disassembled figure would look like when the parts were fitted together.

Directions: Write in the letter of the figure which shows the parts correctly fitted together.



For this test, what method(s) or strategies did you attempt? Describe each. How did you determine whether figures were the same or different?

Which strategy (method) seemed to be most successful for you?

There are individual differences in how we think. Some people think with words and others think with images (pictures of things in their "mind's eye"). Think back to taking this test, and circle the best description given below:

When you were comparing the comparison and test figures, overall to what degree could you "see in your mind's eye" the specific figure?

1 ---------------- 2 --------------- 3 ------------- 4 -------------- 5 ------------- 6 ---------------- 7

1	2	3	4	5	6	7
Never	Once in a while	Somewhat	Half & Half	More so	Pretty much	Always

PLEASE COMPLETE THIS PAGE BEFORE GOING ON AND DO NOT TURN BACK

Two common strategies, in addition to others, that have been reported in the past are a holistic and a detail strategy. Both strategies have been found to be effective on many tests of spatial ability.

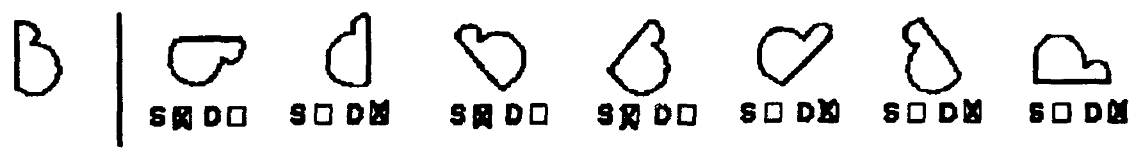
A description of the two strategies is given below. After reading these descriptions please estimate the percentage of time that you used each strategy. **CONSIDER EACH TEST SEPARATELY.**

HOLISTIC STRATEGY: Looking at each figure, shape or pattern as a whole and comparing them to each other; rotating each as a whole and deciding if they are the same or different.

DETAIL STRATEGY: Looking at *parts* of one figure, shape, or pattern and comparing it to parts of the other; like looking at a specific angle or part of the pattern or shape and comparing it to a specific part of the other.

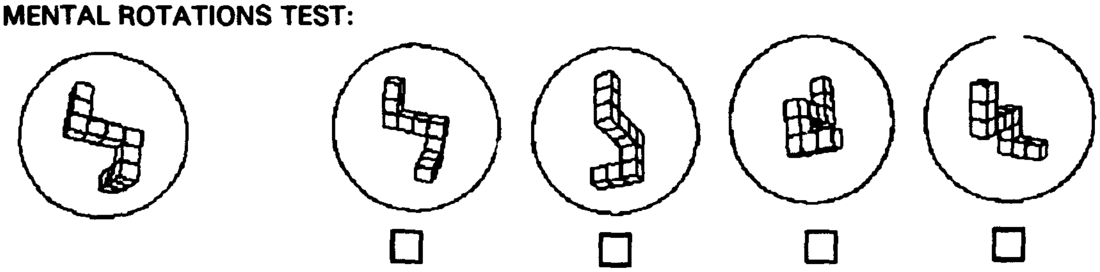
For each test, estimate the percentage of time, out of 100%, you used each strategy. A sample question from each test is given.

CARD ROTATIONS TEST:



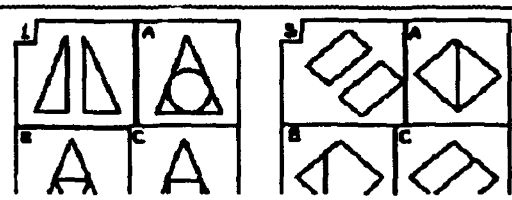
Holistic strategy: _____%   Detail strategy: _____%   Other strategy: _____%

MENTAL ROTATIONS TEST:



Holistic strategy: _____%   Detail strategy: _____%   Other strategy: _____%

PAPER FORMBOARD TEST:



Holistic strategy: _____%   Detail strategy: _____%   Other strategy: _____%

Other research has identified three types of solution strategies for spatial problems. These strategies have also been found to be effective on many tests of spatial ability

Descriptions of these strategies are given below. After reading these descriptions, please mark which strategy you used on each test, if any. Again, CONSIDER EACH TEST SEPARATELY.

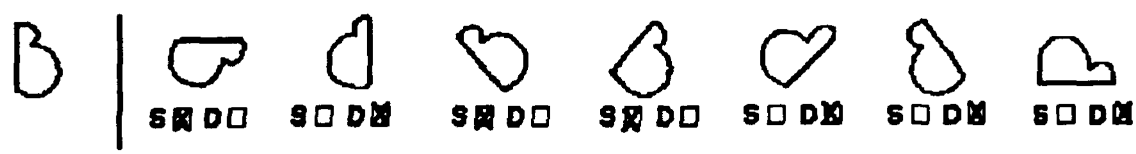
MOVE OBJECT: To solve this task, did you imagine moving the object(s) (for example, twisting, turning rotating)?

MOVE SELF: To solve this task, did you imagine yourself moving around the test object(s) or moving through space (for example, walking, floating)?

KEY FEATURE: To solve this task, did you find a key feature (e.g. size, angle, position, shape, etc.) of the problem and without moving the object or yourself, note whether it was present or how it changed?

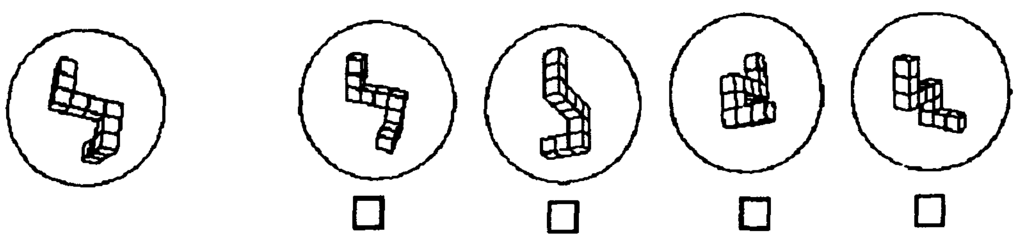
For each test, check which of the above described strategies, if any, you used when solving the problems.

CARD ROTATIONS TEST:



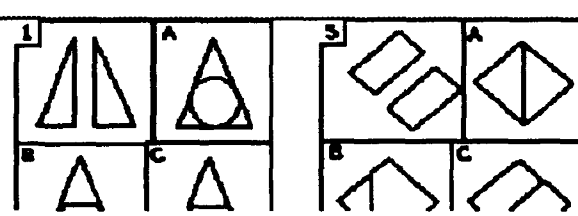
MOVE OBJECT ____ MOVE SELF ____ KEY FEATURE ____ OTHER ____

MENTAL ROTATIONS TEST:



MOVE OBJECT ____ MOVE SELF ____ KEY FEATURE ____ OTHER ____

PAPER FORMBOARD TEST:



MOVE OBJECT ____ MOVE SELF ____ KEY FEATURE ____ OTHER ____

Appendix D. Computer Displayed Instructions

1. Familiarization Block

1.1 Screen 1: Overall Instructions

"This experiment examines your ability to see differences in figures. You will be asked to compare pairs of figures, presented one at a time. The first figure will be displayed for about 2 seconds. Memorize it. Then the second figure will automatically flash up, and you are to determine whether the second figure is the same or different from the first one.

The figures may vary in their angular orientation, and you have to take this into account. The figures are considered the same if they would match one another under the same orientation. The figures are considered different if they are mirror reflections of one another. Press the '1' key on the keypad if they are the same, and the '2' key if they are different.

For example:

The second figure is the SAME.
(Press the '1' key.)

The second figure is a MIRROR.
(Press the '2' key.)

Please press the spacebar to continue."

1.2 Screen 2: Instructions continued

"Rest your index finger above the '1' key on the KEYPAD, and your middle finger above the '2' key. As soon as the second figure is presented, press '1' if the figures

are the SAME, and '2' if the figures are DIFFERENT (i.e., mirrored reflections of each other).

Respond as quickly as possible without making many errors. Your score is based on BOTH response time and accuracy.

We will start with 10 practice trials. After a pause. there will be three blocks of 96 trials each. You must get at least 80% of the practice trials correct to begin the experiment.

If you have any questions ask the experimenter now.

Press the spacebar to begin."

<u>1.3 Screen 3: Warning that Actual Trials are to Begin</u>

"Now that you have satisfactorily completed the practice trials, you are ready to begin the experiment. The following set of trials will be exactly the same as the practice trials you just completed. This portion of the experiment is comprised of 3 blocks of 96 trials each.

If you have any questions, please ask the experimenter now.

Work as quickly and as accurately as you can.

Try to maintain a 95% accuracy rate on these trials.

Press the spacebar to begin the experiment."

<u>1.4 Screen 4: Inter-trial Interval and Focus</u>

"Get Ready

+

Trial X of 96"

1.5 Screen 5: First Stimuli

[First figure appears in center of screen]

"You have about 2 seconds to study the figure"

1.6 Screen 6: Test Stimuli

[Second figure appears in center of screen]

"Press: 1 for matching images; 2 for mirror images"

1.7 Screen 7: Feedback

If correct:

"Correct Response!

X.XX Response Time In Seconds

XX.XX% Average Percent Correct"

If incorrect:

"Wrong Response!" [+ 400ms-long tone]

1.8 Screen 8: Pause

"You have performed XX of 96 trials. You may take a brief pause now before continuing.

Your accuracy is XX%."

[if < 90%, then:] "Please try to increase your accuracy to at least 90%."

[if => 90%, then:] "Which is good. Keep it up!"

"Press the spacebar when you are ready to begin"

2. Single-Task Block

2.1 Screen 1: Initial instructions

"This block of trials is exactly the same as the first set you performed. You are to determine whether the second

figure is the same or different from the first figure.

Rest your index finger above the '1' key on the KEYPAD, and your middle finger above the '2' key. As soon as the second figure is presented, press '1' if the figures are the SAME, and '2' if the figures are DIFFERENT (i.e., mirrored reflections of each other).

Respond as quickly as possible without making many errors. You score is based on BOTH response time and accuracy.

If you have any questions ask the experimenter now.

Press the spacebar to begin."

[***NOTE:*** *All other screens are the same as in the Familiarization Block.*]

3. Dual-Task Block

3.1 Screen 1: Initial Instructions

"The following block of trials is slightly different from the previous block. In addition to determining if the figures are same or different, you will be given a set of six digits to rehearse.

WHILE YOU ARE DOING THE FIGURE COMPARISON TRIALS, repeat the digits over and over out loud, under your breath, until you are asked to type them into the computer. After you have typed them in, you will be given a new set of digits. This will happen every six trials.

Continue to respond to the figures as you have been

doing, as quickly and as accurately as you can.

If you have any questions, please ask the experimenter now.

Work as quickly and as accurately as you can.

Try to maintain a 95% accuracy rate on these trials!

Press the spacebar to begin the trials."

<u>3.1 Screen 2: Digit Presentation</u>

"Your accuracy on the SAME/DIFFERENT judgements is XX%.

[see 1.8 Screen 8 above]

Please rehearse the following digits in order, and repeat them as you perform the following trials:

XXXXXX

Press spacebar when you are ready to continue.

(Rest you fingers in the ready position above the '1' and '2' keys.)"

<u>3.2 Screen 3: Digit Response</u>

"Please type in the digits you have been rehearsing, in order:

(Use 'BACKSPACE' to change your answer, if necessary. Make sure you have entered the digits correctly before pressing 'enter').

Press 'enter' when you are finished."

[Feedback ("Correct Response!" or "Incorrect Response!" is presented after subject presses enter. Then the Digit Presentation screen is displayed.]

[***NOTE:*** *Screens for Rotation Trials are the same as above.*]

Appendix E. Post-task Strategy Questionnaire

Strategies Questionnaire

NAME: ______________________________ **SSN:** ______________________

In the computer-based spatial task you just performed, you were required to compare objects of different angular orientations.

1. Describe in your own words *what procedure* you used in deciding whether the pairs of shapes were the same or mirror reflections of one another. Indicate whether your chosen strategy changed over time or not.

SPATIAL TASK ALONE:

TASK + DIGIT MEMORIZATION:

PLEASE COMPLETE THIS PAGE BEFORE GOING ON TO THE NEXT.

2. Two common strategies, in addition to others, that have been reported in the past are a holistic and a detail strategy. Both strategies have been found to be effective on many tests of spatial ability.

A description of the two strategies is given below. After reading these descriptions please estimate the percentage of time that you used each strategy. **CONSIDER EACH TASK SEPARATELY.**

HOLISTIC STRATEGY: Looking at each figure, shape or pattern as a whole and comparing them to each other; rotating each as a whole and deciding if they are the same or different.

DETAIL STRATEGY: Looking at *parts* of one figure, shape, or pattern and comparing it to parts of the other; like looking at a specific angle or part of the pattern or shape and comparing it to a specific part of the other.

For each task, estimate the percentage of time, out of 100%, you used each strategy.

SPATIAL TASK ALONE:

Holistic strategy: ____%   Detail strategy: ____%   Other strategy: ____%

TASK + DIGIT MEMORIZATION:

Holistic strategy: ____%   Detail strategy: ____%   Other strategy: ____%

PLEASE COMPLETE THIS PAGE BEFORE GOING ON TO THE NEXT.

3. Other research has identified three types of solution strategies for spatial problems. These strategies have also been found to be effective on many tests of spatial ability

Descriptions of these strategies are given below. After reading these descriptions, please mark which strategy you used on each test, if any. Again, **CONSIDER EACH TASK SEPARATELY.**

MOVE OBJECT: To solve this task, did you imagine moving the object(s) (for example, twisting, turning rotating)?

MOVE SELF: To solve this task, did you imagine yourself moving around the test object(s) or moving through space (for example, walking, floating)?

KEY FEATURE: To solve this task, did you find a key feature (e.g. size, angle, position, shape, etc.) of the problem and without moving the object or yourself, note whether it was present or how it changed?

For each task, check which of the above described strategies, if any, you used when solving the problems, and estimate the percentage of time you used each.

SPATIAL TASK ALONE:

MOVE OBJECT ____ MOVE SELF ____ KEY FEATURE ____ OTHER ____

TASK + DIGIT MEMORIZATION:

MOVE OBJECT ____ MOVE SELF ____ KEY FEATURE ____ OTHER ____

PLEASE COMPLETE THIS PAGE BEFORE GOING ON TO THE NEXT.

4. Please estimate the percentage of time that you ***rotated*** a mental image of one or both of the polygons in order to compare the pair.

SPATIAL TASK ALONE: ______%

TASK + DIGIT MEMORIZATION: ______%

5. Please estimate the percentage of time you ***flipped*** a mental image of one or both of the polygons in order to compare the pair.

SPATIAL TASK ALONE: ______%

TASK + DIGIT MEMORIZATION: ______%

6. Please estimate the amount of *mental effort* you exerted while performing the tasks on a scale from 0 to 10, where 0 represents absolutely no effort at all, and 10 represents the maximum effort you are able to exert.

SPATIAL TASK ALONE: ______

TASK + DIGIT MEMORIZATION: ______

Thank you for your participation!

Appendix F. ANOVA Tables

Table 1. *2(Skill) x 2(Gender) ANOVA on Number of Practice Blocks*

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG OF F
SKILL	37.90	1	37.90	11.22	.002
GENDER	5.93	1	5.93	1.76	.191
SKILL x GENDER	14.03	1	14.03	4.15	.047
Residual	162.18	48	3.38		
Total	220.08	51	4.32		

Table 2. *Repeated Measures MANOVA on Mean Response Time at Each Angle, using Skill, Gender, Skill x Gender, and Task Condition nested w/in Skill x Gender as Between-Subject Effects; and Angle as the Within-Subject Factor*

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG OF F
Between-Subjects Effects:					
TASK CONDITION	418855.95	4	104713.99	.	.733
GENDER	6346827.20	1	6346827.20	30.54	.000
SKILL	8889203.49	1	8889203.49	42.77	.000
GENDER x SKILL	1975379.04	1	1975379.04	9.50	.003
Residual	19743655.03	95	207827.95		

Within-Subject Effects:
(Mauchly sphericity test W = .401; $\chi^2(14) = 85.11$, $p < .001$)

Hoetellings F-tests:

EFFECT	VALUE	DF	F	SIG OF F
ANGLE	3.400	(5,91)	61.89	.000
TASK CONDITION x ANGLE	.108	(20,358)	.48	.972
GENDER x ANGLE	.227	(5,91)	4.13	.002
SKILL x ANGLE	.369	(5,91)	6.71	.000
GENDER x SKILL x ANGLE	.120	(5,91)	2.18	.063

Table 3. *2(Skill) x 2(Gender) Repeated Measures MANOVA on Difference Scores (Single-Task RT minus Dual-Task RT) at Each Angle, with Angle as the Within-Subject Factor*

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG OF F
Between-Subjects Effects:					
GENDER	571018.89	1	571018.89	4.50	.039
SKILL	136074.08	1	136074.08	1.07	.305
GENDER x SKILL	44386.21	1	44386.21	.35	.557
Residual	6084137.63	48	126752.87		

Within-Subject Effects:
(Mauchly sphericity test W = .205; $\chi^2(14) = 73.02$, $p < .001$)

Hoetellings F-tests:

EFFECT	VALUE	DF	EXACT F	SIG OF F
ANGLE	.085	(5,44)	.75	.592
GENDER x ANGLE	.122	(5,44)	1.07	.389
SKILL x ANGLE	.141	(5,44)	1.24	.308
GENDER x SKILL x ANGLE	.067	(5,44)	.59	.709

Table 4a. *2(Skill) x 2(Gender) ANOVA on Single-Task Slope*

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG OF F
SKILL	25.10	1	25.10	7.88	.007
GENDER	26.54	1	26.54	8.34	.006
SKILL x GENDER	19.25	1	19.25	6.05	.018
Residual	152.81	48	3.18		
Total	223.70	51	4.39		

Table 4b. *2(Skill) x 2(Gender) ANOVA on Single-Task Intercept*

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG OF F
SKILL	121516.85	1	121516.853	5.93	.019
GENDER	192053.31	1	192053.31	9.36	.004
SKILL x GENDER	2998.25	1	2998.25	.15	.704
Residual	984409.95	48	20508.54		
Total	1300978.36	51	25509.38		

Table 4c. *2(Skill) x 2(Gender) ANOVA on Dual-Task Slope*

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG OF F
SKILL	20.74	1	20.74	7.66	.008
GENDER	15.65	1	15.65	5.78	.020
SKILL x GENDER	7.80	1	7.80	2.88	.096
Residual	130.00	48	2.71		
Total	174.19	51	3.42		

Table 4d. *2(Skill) x 2(Gender) ANOVA on Dual-Task Intercept*

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG OF F
SKILL	259691.21	1	259691.21	13.80	.001
GENDER	66589.27	1	66589.27	3.54	.066
SKILL x GENDER	11044.70	1	11044.70	.59	.447
Residual	903523.83	48	18823.41		
Total	1240849.01	51	24330.37		

Table 5. *2(Order) x 2(Skill) x 2(Gender) x 6(Angle) ANOVA on Number of Errors*

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG OF F
ORDER	4.09	1	4.09	2.72	.100
SKILL	102.88	1	102.88	68.45	.000
GENDER	26.41	1	26.41	17.57	.000
ANGLE	100.39	5	20.08	13.36	.000
ORDER x SKILL	.01	1	.01	.00	.952
ORDER x GENDER	.62	1	.62	.41	.520
ORDER x ANGLE	11.17	5	2.23	1.49	.192
SKILL x GENDER	6.76	1	6.76	4.50	.034
SKILL x ANGLE	25.47	5	5.09	3.39	.005
GENDER x ANGLE	18.16	5	3.63	2.42	.035
ORDER x SKILL x GENDER	.00	1	.00	.00	.968
ORDER x SKILL x ANGLE	4.28	5	.86	.57	.723
ORDER x GENDER x ANGLE	1.96	5	.39	.26	.935
SKILL x GENDER x ANGLE	9.85	5	1.97	1.31	.258
ORDER x SKILL x GENDER x ANGLE	.00	5	1.19	.79	.554
Residual	865.70	576	1.50		
Total	1183.71	623	1.90		

April, 1994

Vita

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PUBLICATIONS AND PAPERS PRESENTED

Daly, P. K. & Crawford, H. J. (1993, October). Individual differences in mental rotation: Effect of presentation time and working memory load. Poster session presented at the 37th annual meeting of the Human Factors and Ergonomics Society, Seattle, WA.

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4 USAF Job Inventories (1991-1992) [for Fire Protection, Aircraft Armament Systems, Communications-Computer Systems Control, and Electrical-Environmental Systems specialties]

25 USAF Specialty Knowledge Tests (1988-1990)

Editor of The Dodo, USAF Academy cadet humor magazine (1987-1988)

SIGNED: Paul [signature] **DATE:** 1 May 94